

# Electromagnetic Churning of Laser Melt-Pool in Metal 3D Printing

Oleksii Karpenko, Satish Udpa, Mahmood Haq and Lalita Udpa

Michigan State University  
Composite Vehicle Research Center

[karpenko@msu.edu](mailto:karpenko@msu.edu)  
517-402-0634

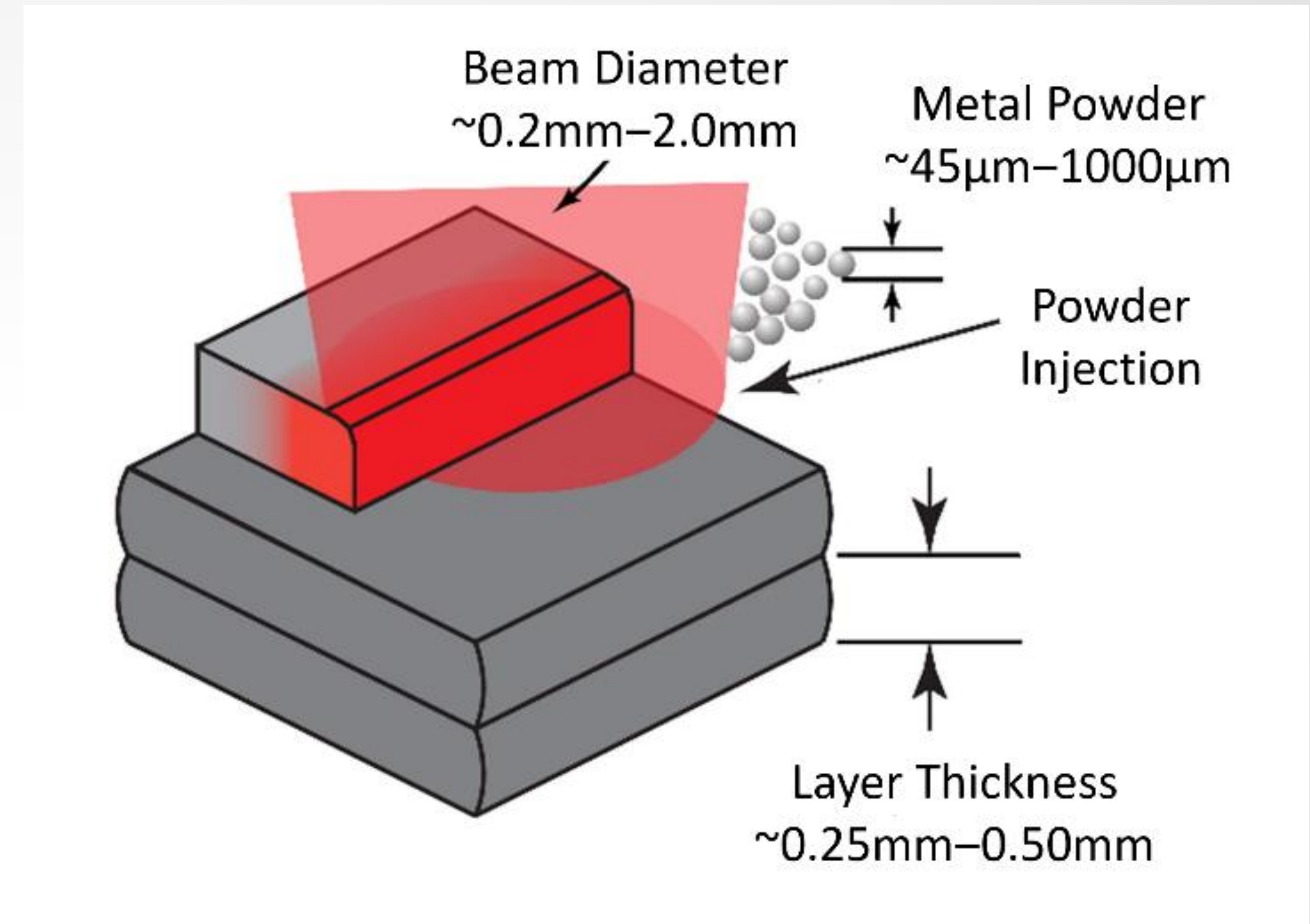
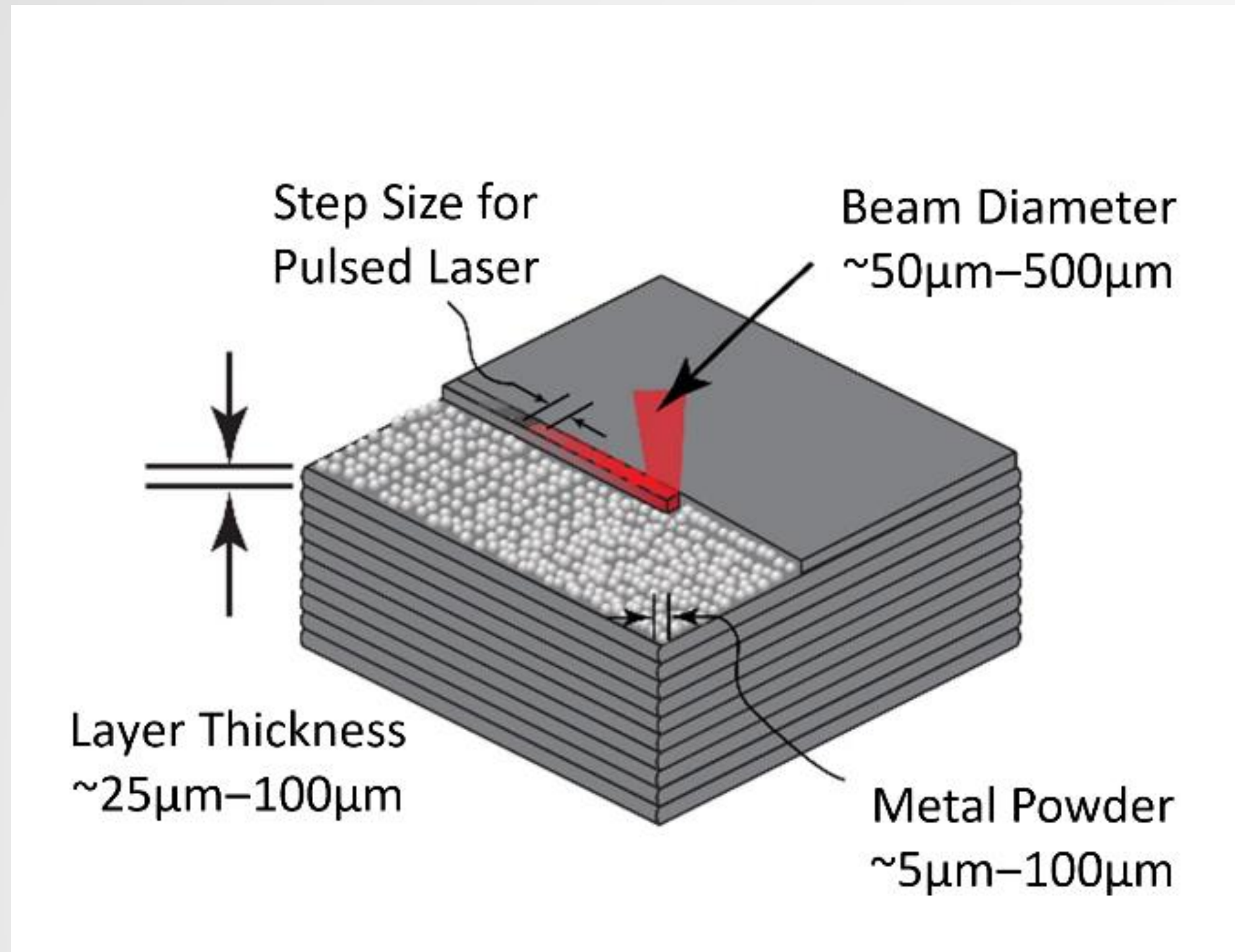


# Metal Additive Manufacturing (MAM) in U.S. Army

- **On-Demand Manufacturing:** The U.S. Army can produce spare parts for vehicles, aircraft, and other equipment directly in the field or at forward operating bases, reducing the need for large inventories
- **Customization:** Parts can be customized or improved based on specific mission requirements
- **Prototyping and Development:** Army engineers can quickly design, produce, and test prototypes of new equipment or modifications to existing gear
- **Lightweight Structures:** MAM can produce lightweight yet strong components, benefiting applications such as unmanned aerial vehicles (UAVs) and other mobile platforms



# Metal Additive Manufacturing: PBF vs DED

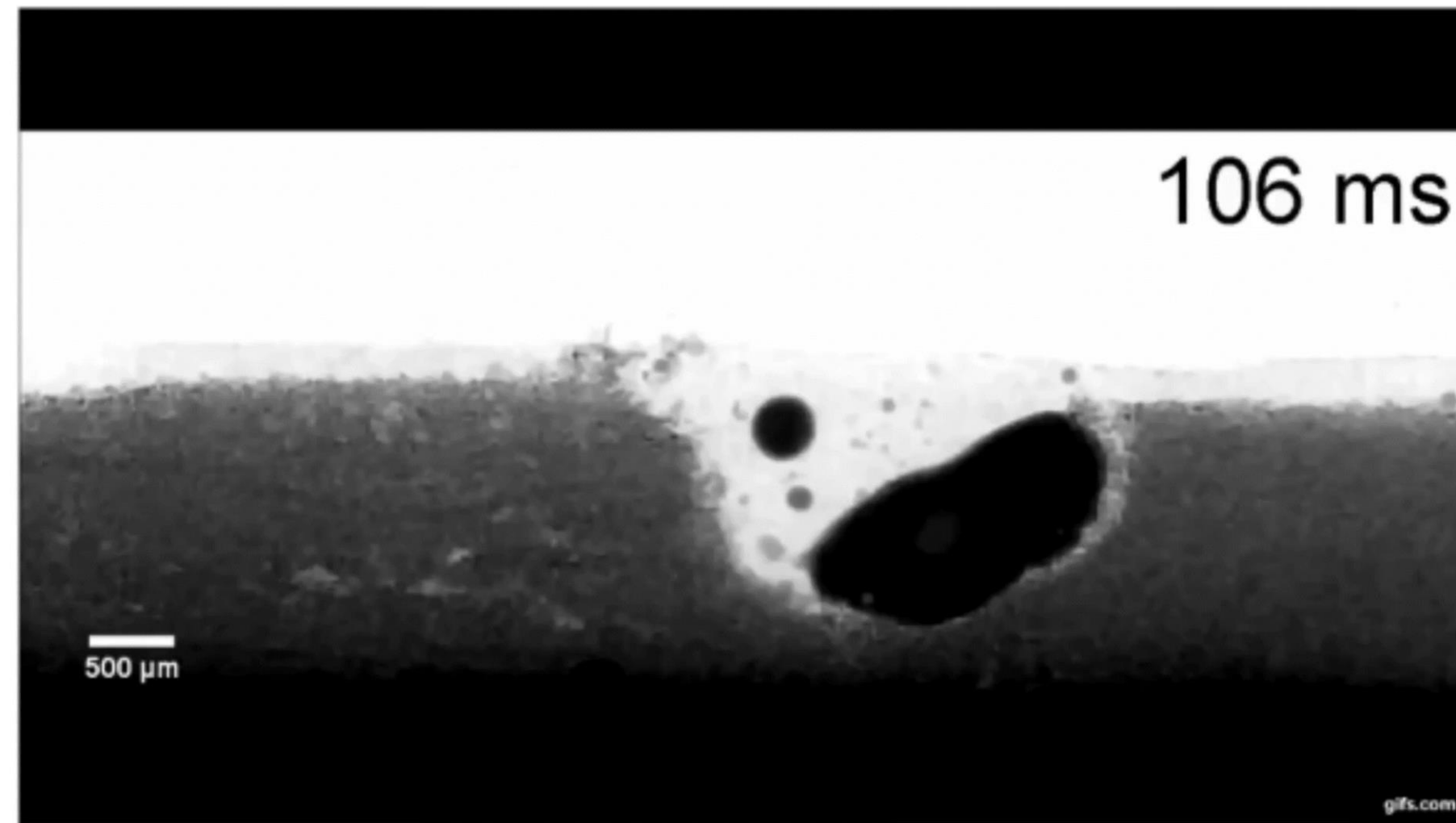


Powder Bed Fusion,  
Selective Laser Melting, Direct Metal Laser  
Sintering

Direct Energy Deposition

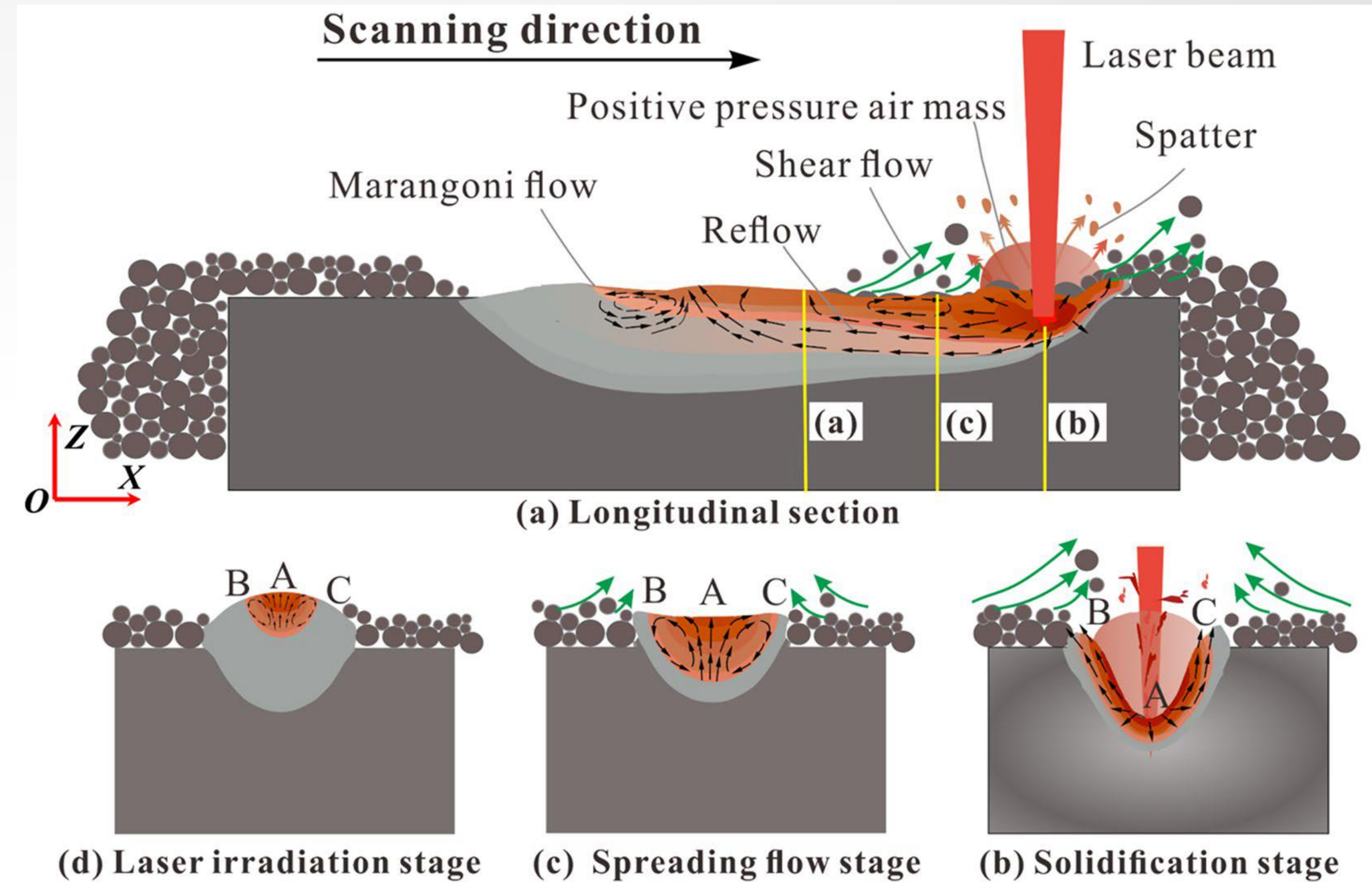


# Metal Additive Manufacturing: Melt-Pool Formation



Leung, C.L.A., et al. Nat Commun **9**, 1355 (2018).  
<https://doi.org/10.1038/s41467-018-03734-7>

## X-ray imaging of melt-pool in PBF



Zhang et al, Chinese Journal of Mechanical Engineering (2023)  
36:32

## Melt-pool formation in the PBF process



# Metal Additive Manufacturing: Challenges

- During the AM processing, various factors, including heating, cooling, or scanning instabilities, can occasionally disrupt the stability of the melt pool, leading to the formation of internal defects
- Defects present in components processed by PBF and DED methods restrict the suitability of MAM for high-performance & safety-critical applications:
  - degraded mechanical & fatigue properties
  - reduced corrosion resistance
  - geometrical inaccuracies & bad surface finish



# Metal Additive Manufacturing: Common Flaws

## COMMON DEFECTS IN METAL ADDITIVE MANUFACTURING

### LACK OF FUSION

- Voids with irregular & elongated shapes (~50 $\mu$ m – 3mm)
- Caused by insufficient hatch spacing & irregular evolution of melt pool during solidification

### KEYHOLE COLLAPSE

- A pore formed at the bottom of melt pool (~10 $\mu$ m – 50 $\mu$ m)
- Occurs in deep V-shaped melt pools due vaporizing elements & improper source power

### GAS POROSITY

- Spherical pores (~5 $\mu$ m – 50 $\mu$ m)
- Caused by gas entrapment, supersaturation of dissolved gases, and chemical reactions within the melt pool

### CRACKING

- Microcracks that occur in the fusion zone near the end of solidification
- Driven by a temperature gradient & complex metallurgical and mechanical factors

### IMPURITIES

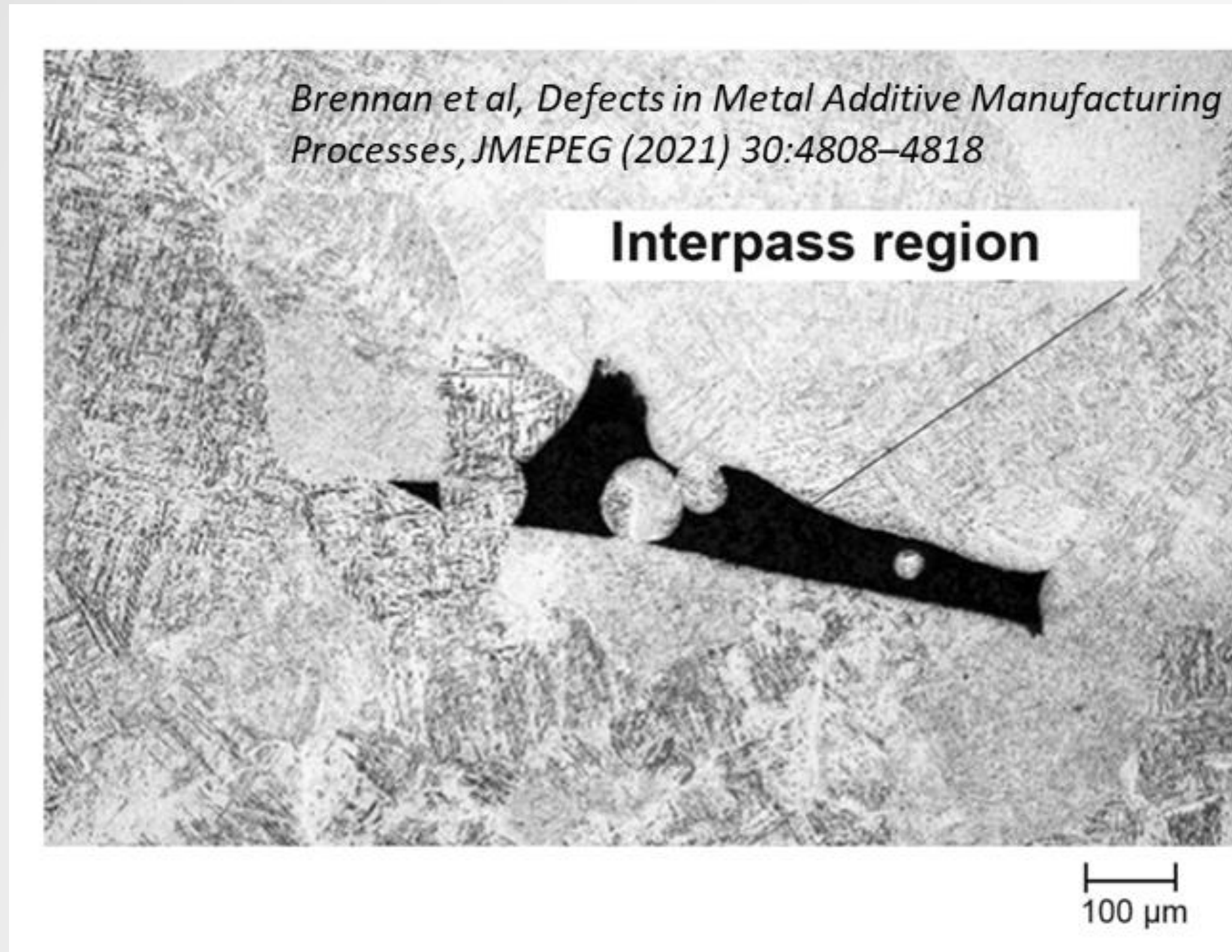
- Excess insoluble elements, such as carbon, oxygen, nitrogen, hydrogen & chlorine
- Introduced when producing & AM processing of metal powder

### OTHER DEFECTS

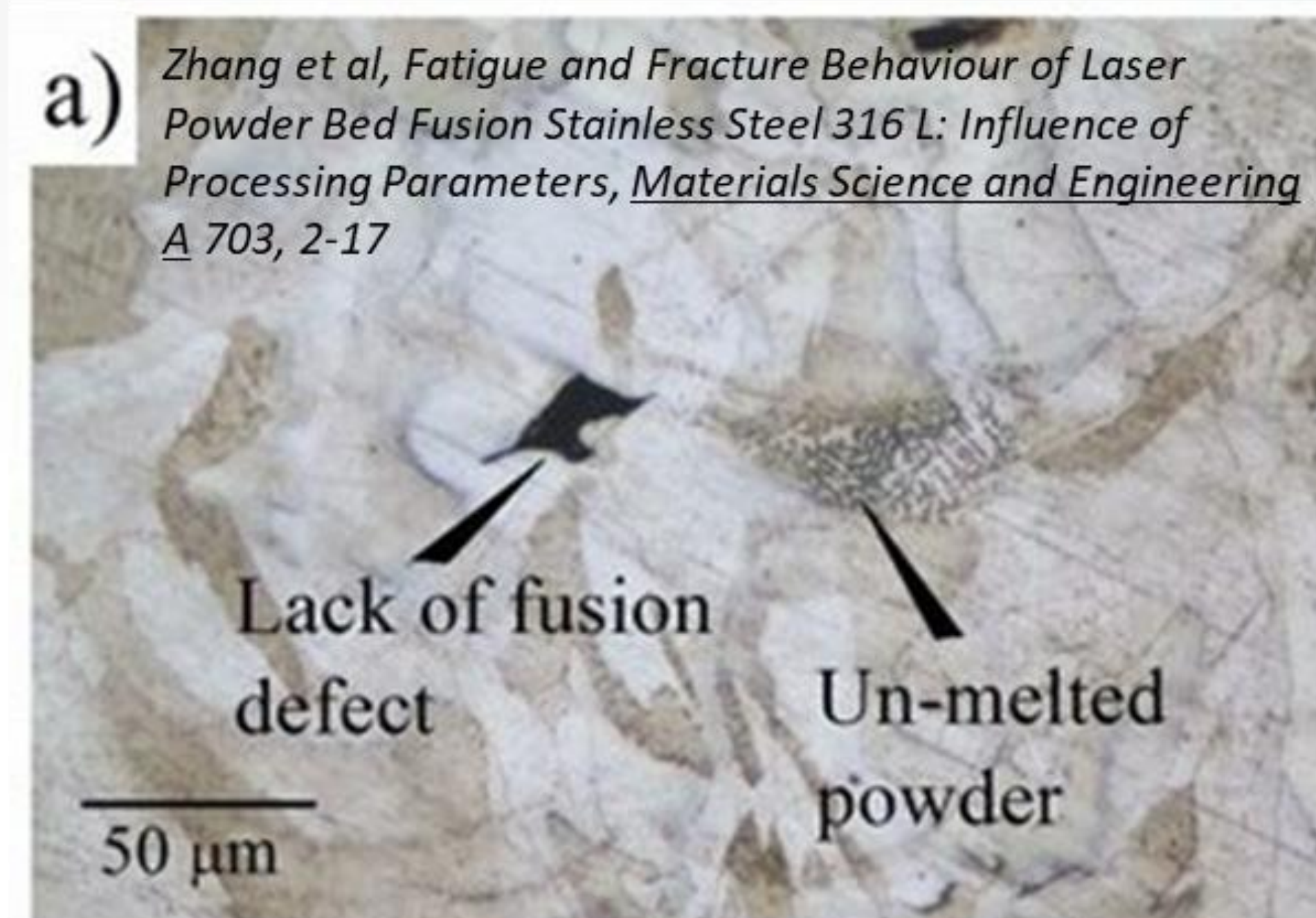
- AM techniques based on Solid-State Sintering exhibit additional types of flaws such as sintering porosities and improper binder burnout



# Common Defects in MAM: Lack of Fusion



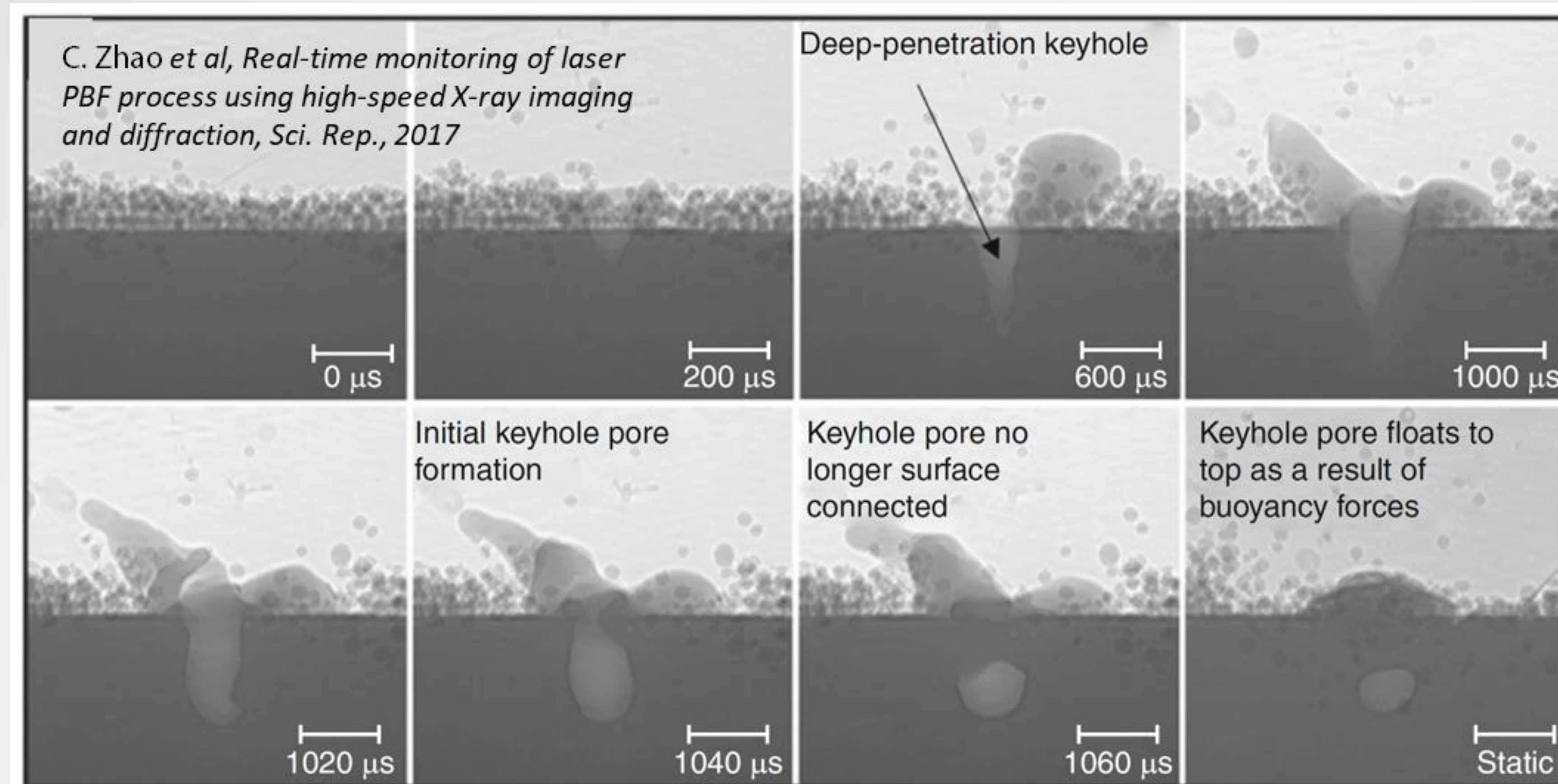
Lack-of-fusion defect formed in a DED-processed Ti-6Al-4V component



Lack of fusion in PBF-processed Stainless Steel 316L



# Common Defects in MAM: Keyholes



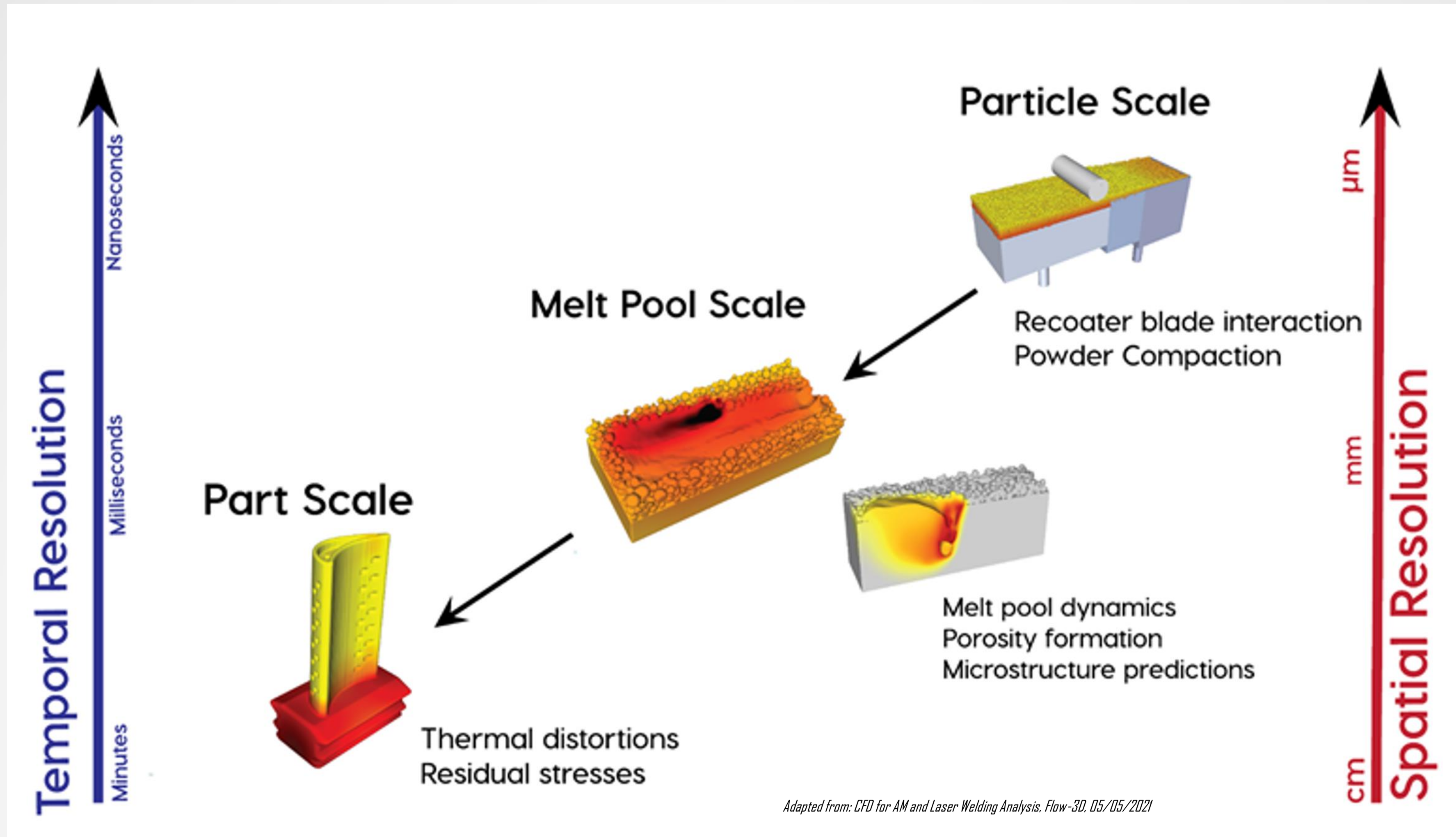
## Dynamic X-ray images of laser PBF processes of Ti-6Al-4V

- A keyhole is formed upon increasing the laser power above the optimal value

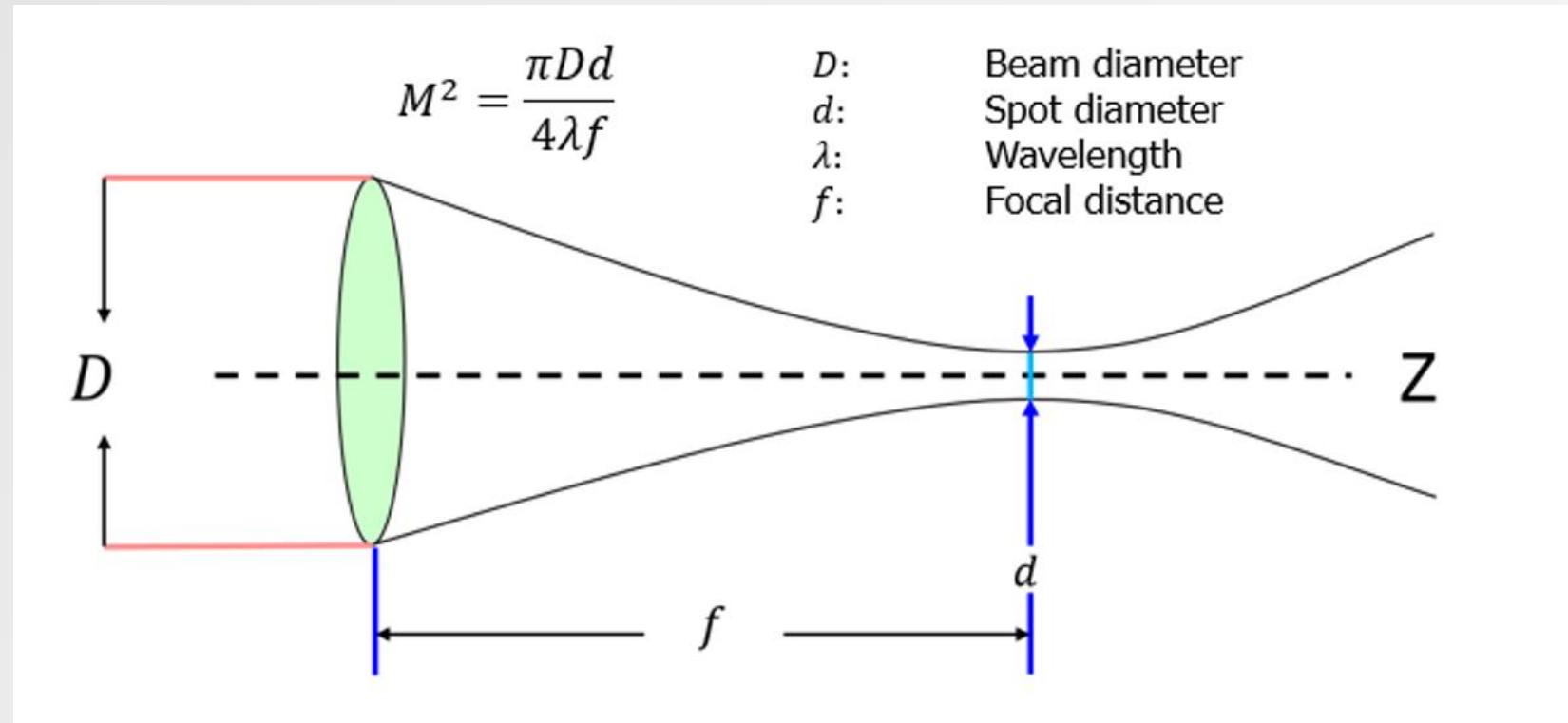




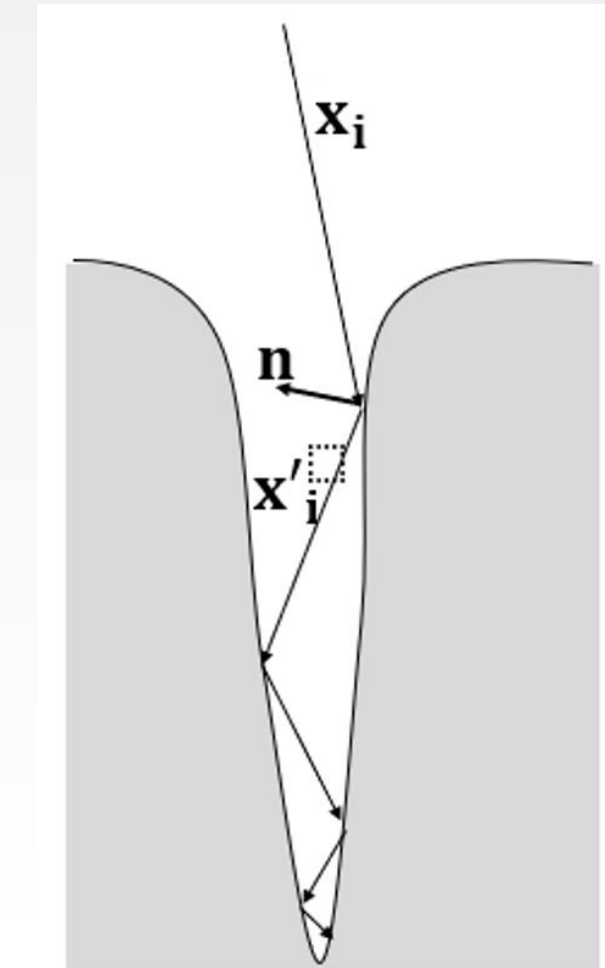
# MAM: Multiphysics Modeling & Different Time/Size Scales



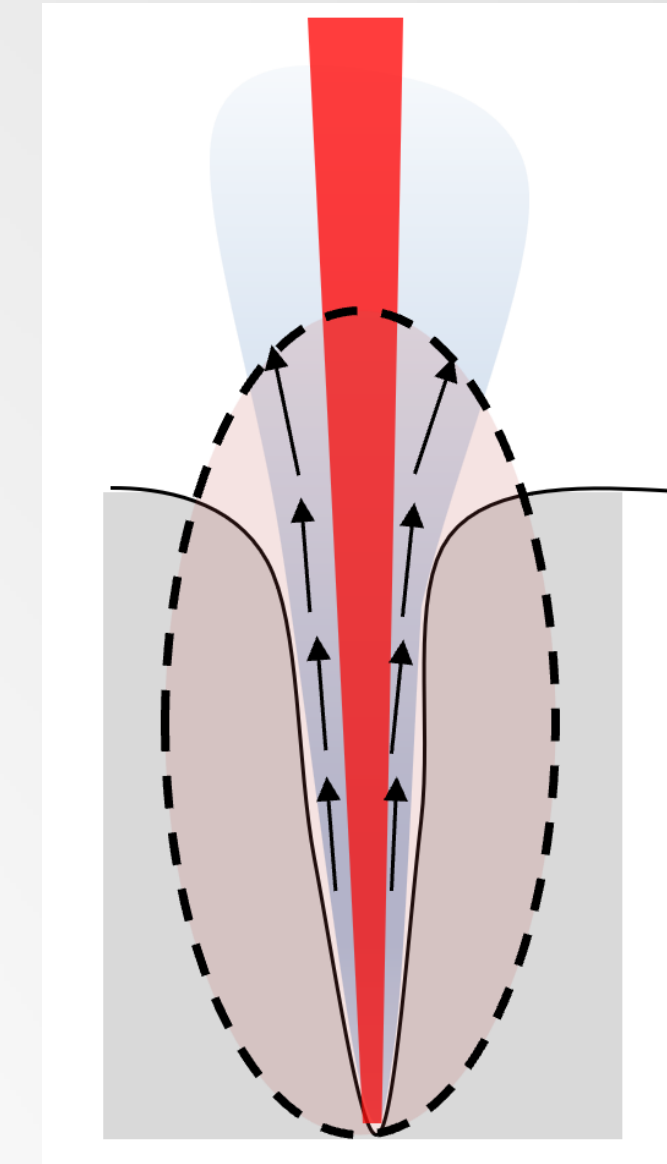
# MAM: Laser Heat Source Interaction with Metal



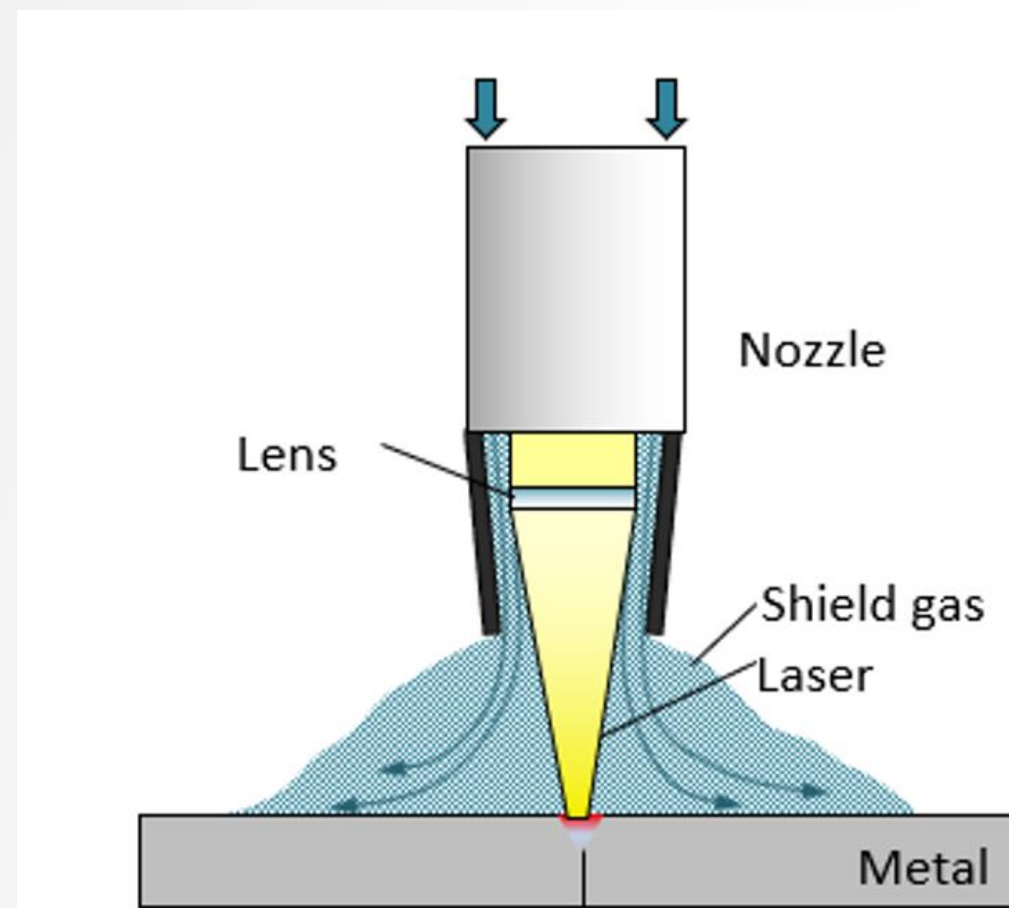
Laser heat flux profile



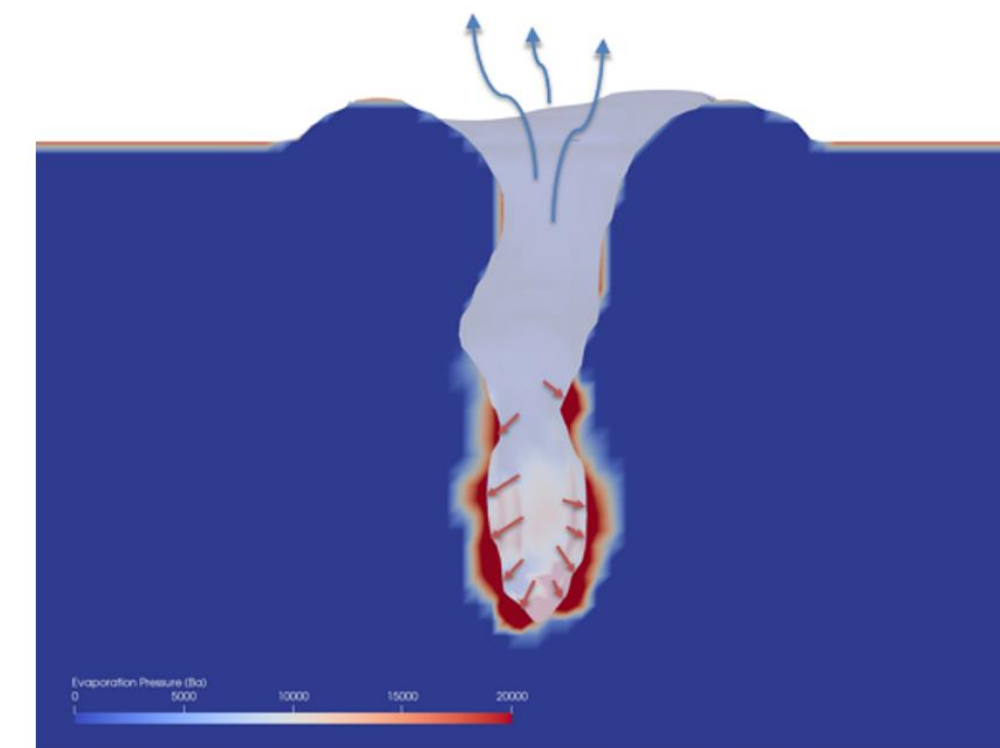
Laser beam reflections



Plume dynamics



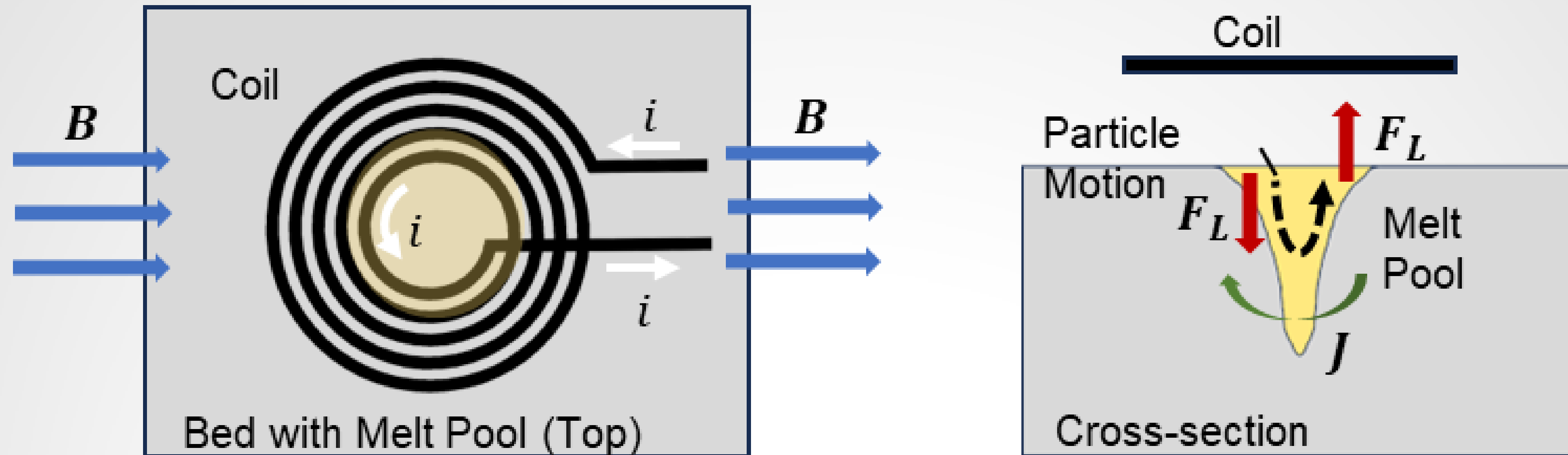
Shield gas pressure



Evaporation pressure



# Electromagnetic Control of Melt-Pool



Coil & permanent magnets for melt-pool churning

$$\text{Lorentz force: } F = J \times B$$



# Melt-Pool Churning: Multiphysics Computational Methods

$$\begin{aligned} \nabla \times \mathbf{H} &= \mathbf{J} \\ \mathbf{B} &= \nabla \times \mathbf{A} \\ \mathbf{J} &= \sigma \mathbf{E} + \mathbf{J}_e \\ \mathbf{E} &= -\frac{\partial \mathbf{A}}{\partial t} \end{aligned}$$

EM Fields

$$\begin{aligned} \mathbf{F} &= \mathbf{J} \times \mathbf{B} \\ \mathbf{J} &= \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \end{aligned}$$

$$\rho \nabla \cdot \mathbf{u} = 0$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot \left( -p\mathbf{I} + (\mu + \mu_T)(\nabla\mathbf{u} + (\nabla\mathbf{u})^T) \right) + \rho\mathbf{g} + \mathbf{F}$$

Mass Transfer

$$\rho C_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot (k \nabla T) = Q$$

Heat Transfer

$$Q = \frac{2P\alpha}{\pi r_b^2} (1 - R) \exp\left(\frac{-2x^2}{r_b^2}\right) \exp(-\alpha z)$$

Laser Energy Source

- $\mathbf{u}$  – velocity field
- $\rho$  – density of fluid (melt-pool)
- $p$  – fluid pressure
- $\mathbf{I}$  – identity tensor
- $\mu$  – fluid dynamic viscosity
- $\mathbf{F}$  – force in the fluid
- $T$  – melt pool temperature,
- $C_p$  – fluid heat capacity at constant  $p$
- $Q$  – heat source energy
- $\mathbf{g}$  – acceleration of free fall
- $\mathbf{F}$  – Lorentz force
- $\mathbf{J}$  – current density induced in the fluid
- $\mathbf{B}$  – magnetic flux density in the fluid
- $\mathbf{E}$  – electric field intensity
- $\mathbf{H}$  – magnetic field intensity
- $P$  – laser output power
- $\alpha$  – absorption coefficient
- $R$  – reflection coefficient
- $r_b$  – effective laser radius



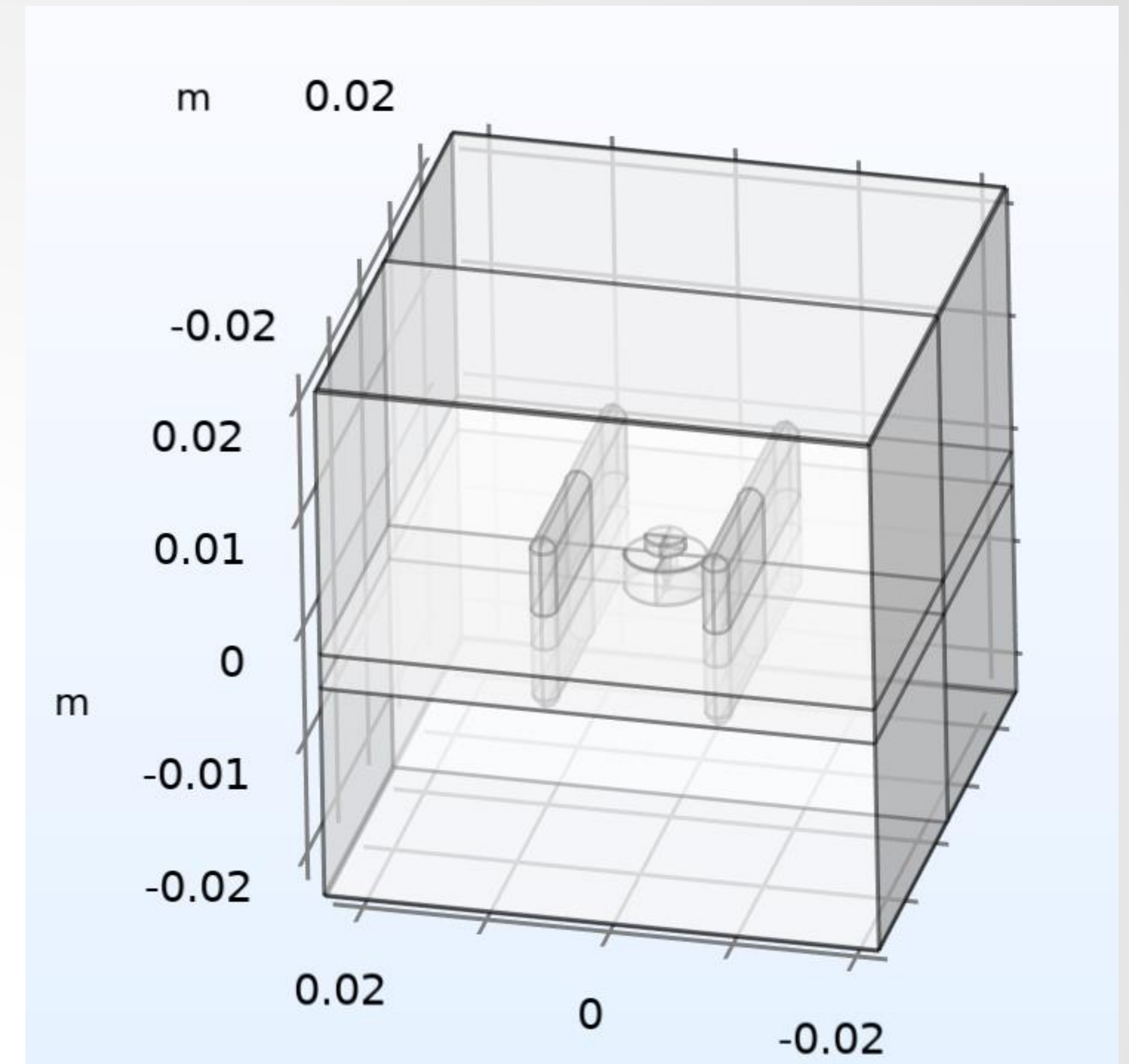
# Melt-Pool Churning Using A Coil: FE Model Geometry

## COMSOL Multiphysics 6.1:

- Magnetic Fields Interface
- Laminar/Turbulent Flow Interface
- Magnetohydrodynamics Effect

## Simulated Set-up:

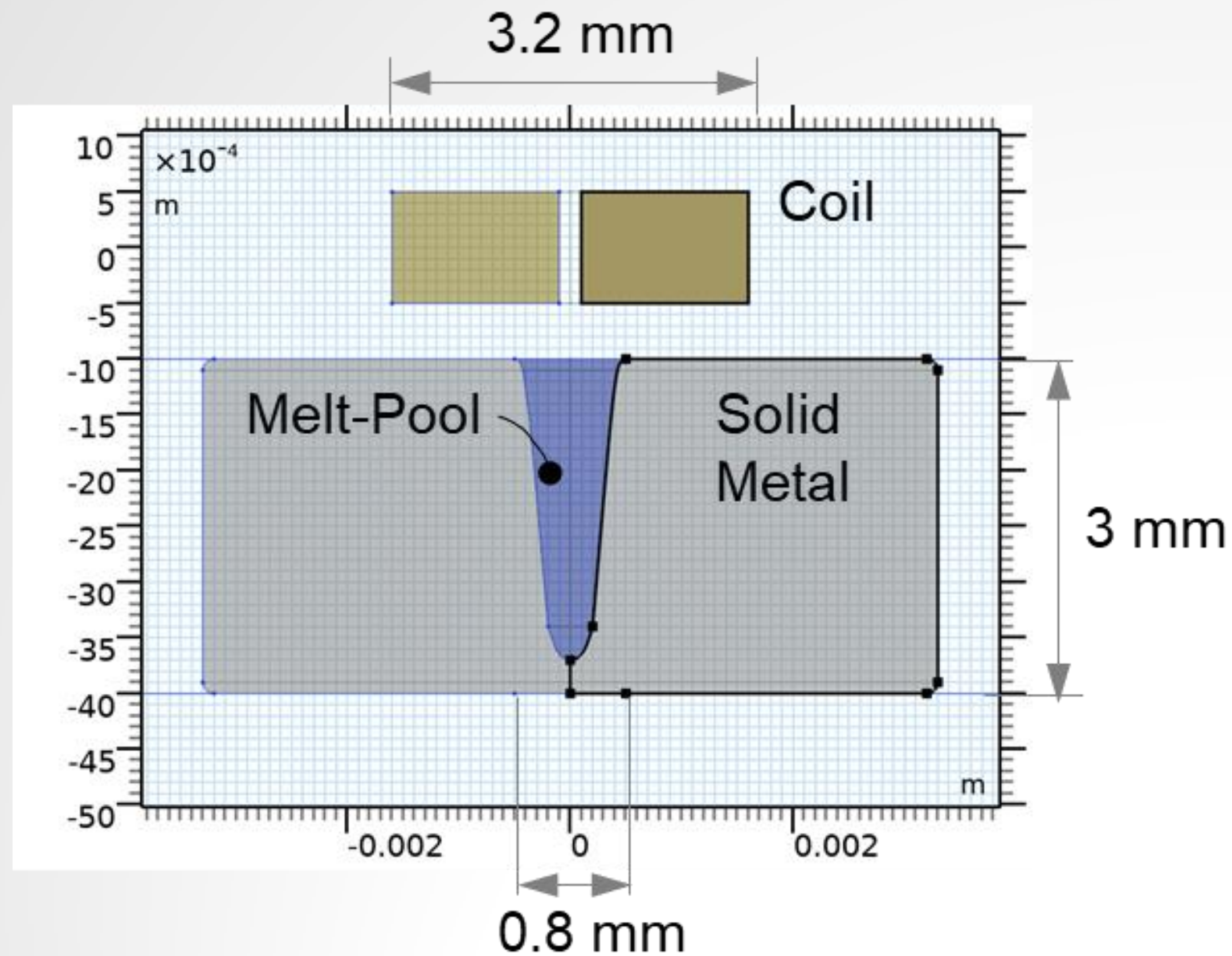
- Melt-pool is simulated as a thin cylinder of molten aluminum
- The thin cylinder is surrounded by a thicker ring of solid metal
- The coil is placed on top of the melt-pool to generate eddy currents
- A pair of bar magnets simulates the DC magnetic field
- The geometric features are sitting in the larger air cube



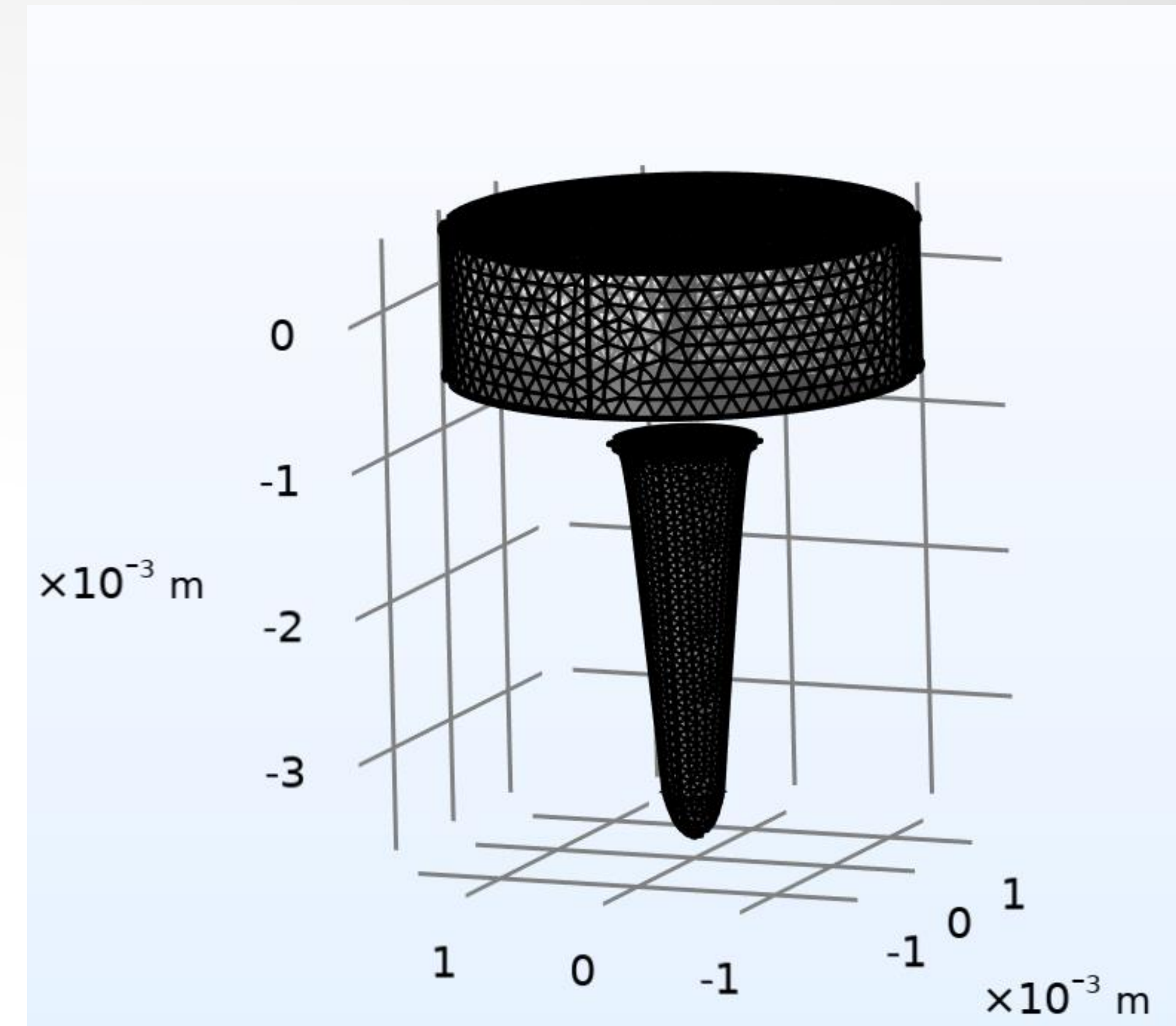
Overall FE model geometry



# Melt-Pool Churning Using A Coil: FE Model Mesh



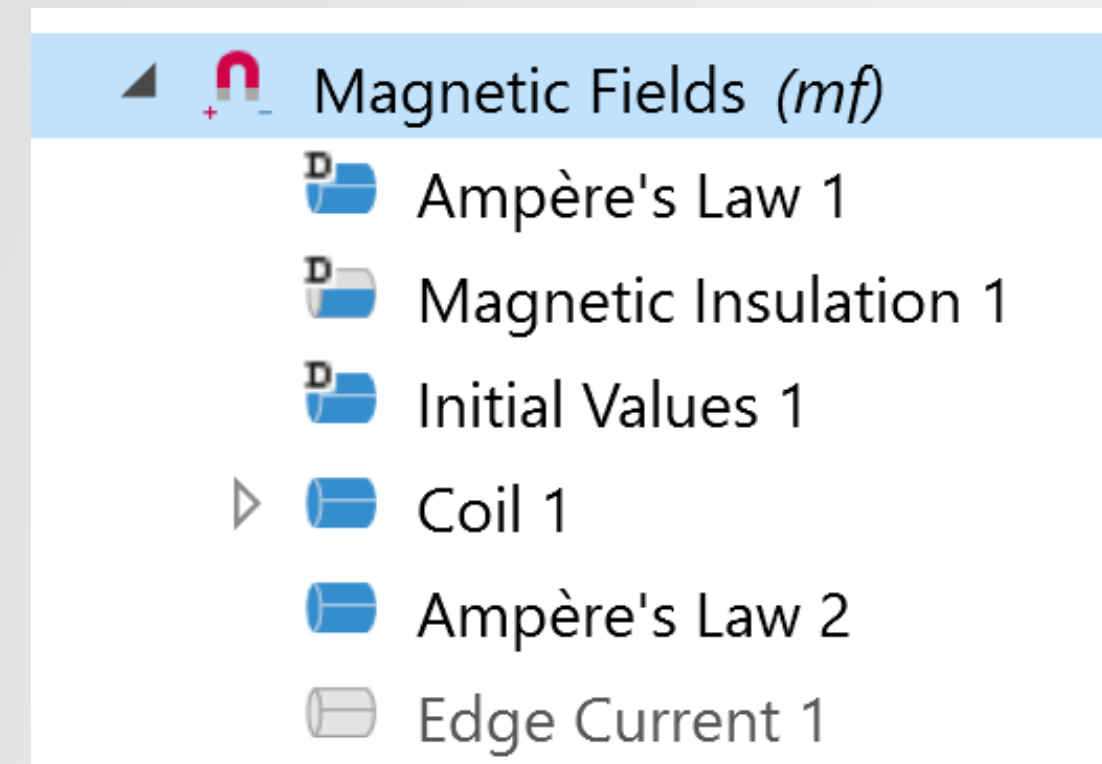
Cross-section geometry of the simulated excitation coil, melt-pool & surrounding solid metal



Tetrahedral mesh of the coil & melt-pool



# Melt-Pool Churning Using A Coil: EM Fields & BC



## COMSOL MF Interface

$$\nabla \times \mathbf{H} = \mathbf{J}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

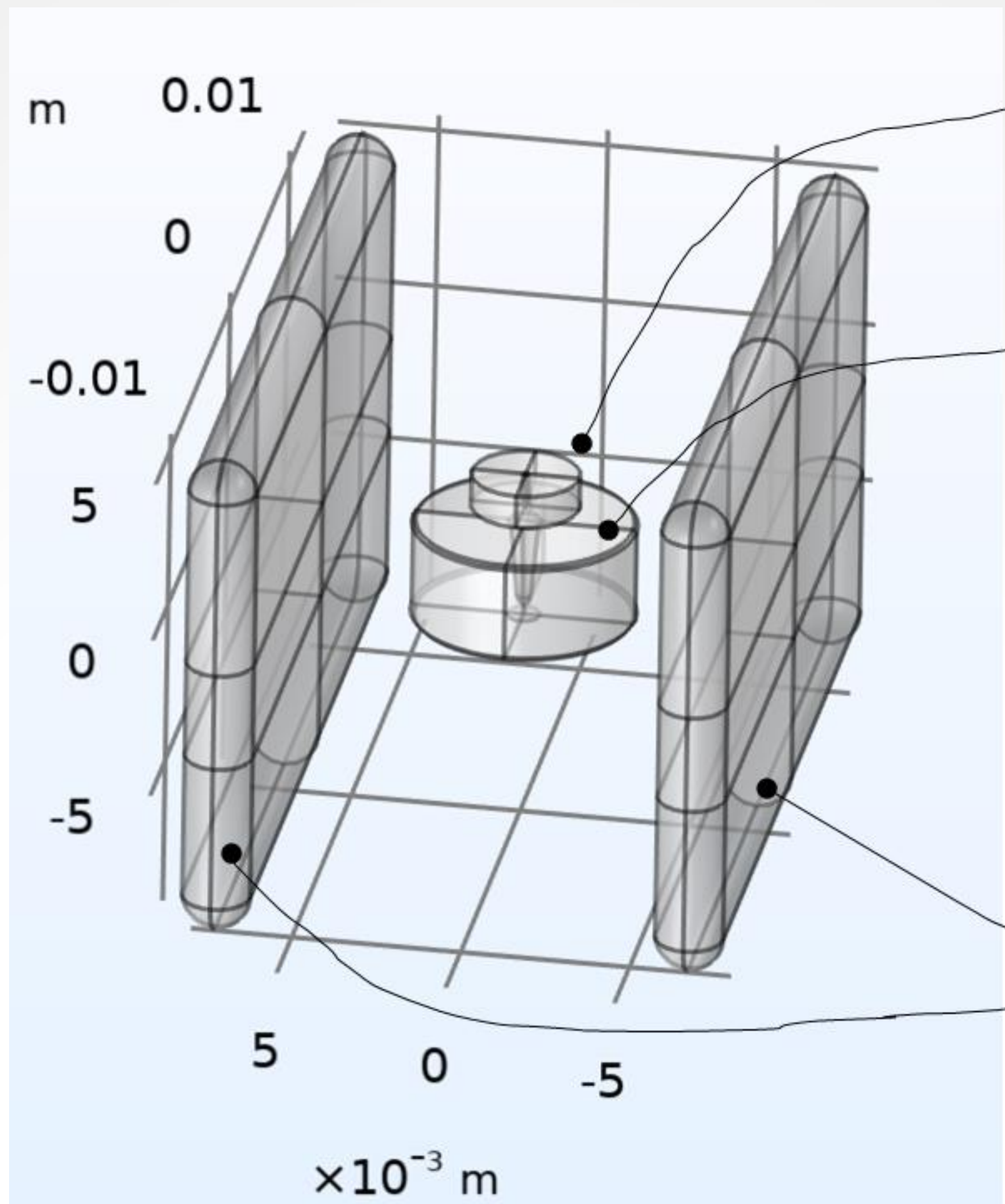
$$\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}_e$$

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t}$$

$$\mathbf{n} \times \mathbf{A} = 0$$

External  
Faces

## Maxwell's Equations



Excitation Coil:  
AC B-field

Solid Metal

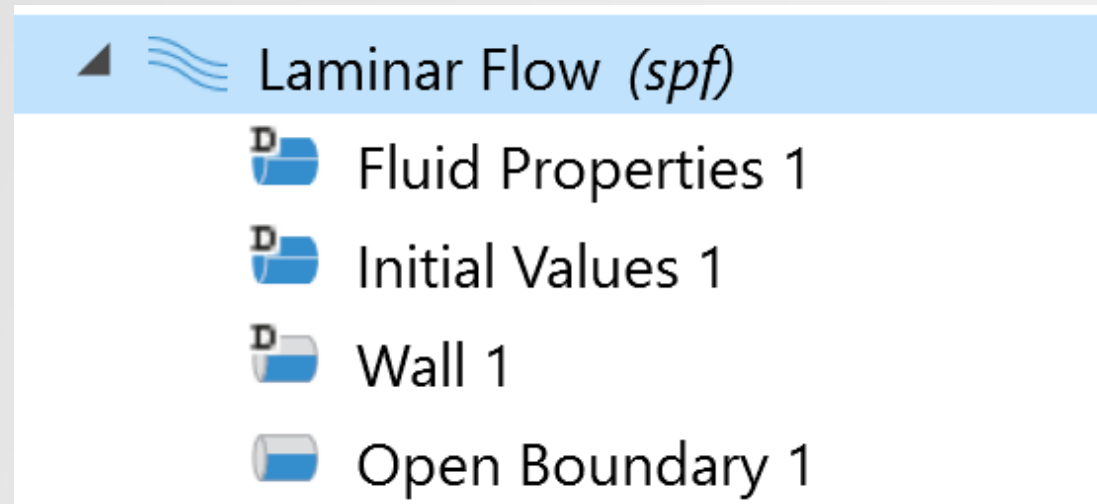
$$\mathbf{B} = \mu_0 \mu_{rec} \mathbf{H} + \mathbf{B}_r,$$

$$\mathbf{B}_r = \|\mathbf{B}_r\| \frac{\mathbf{e}}{\|\mathbf{e}\|} \quad 1 \text{ [T]}$$

Permanent Magnets:  
(DC B-field) in Y-direction



# Melt-Pool Churning Using A Coil: CFD Formulation & BC



## COMSOL Single Phase Flow

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mathbf{K}] + \mathbf{F}$$

$$\rho \nabla \cdot \mathbf{u} = 0$$

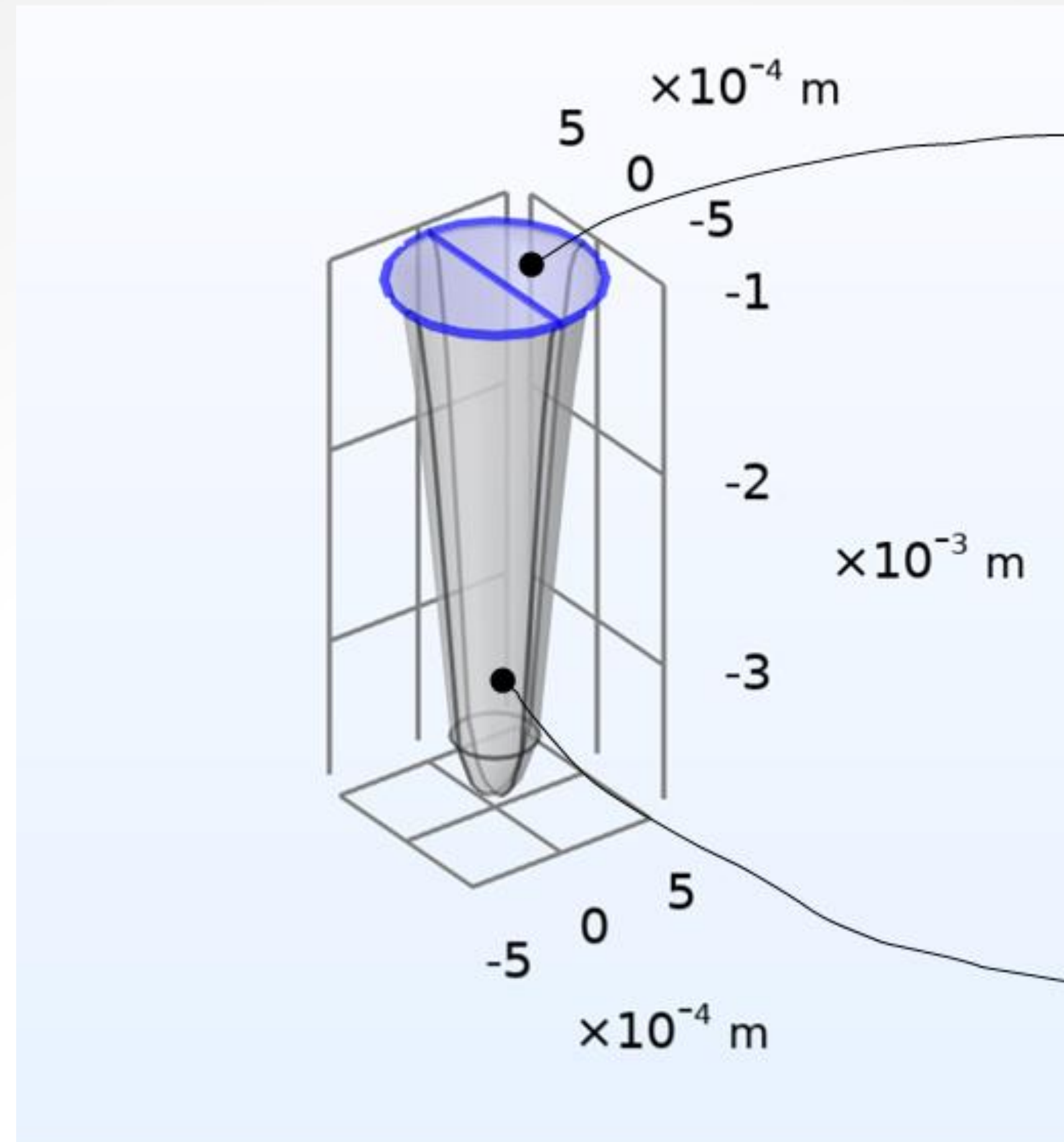
$$\mathbf{K} = \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)$$

## Navier-Stokes Equations

$$\mathbf{F} = \mathbf{J} \times \mathbf{B}$$

$$\mathbf{J} = \sigma (\mathbf{E} + \mathbf{u} \times \mathbf{B})$$

## Magnetohydrodynamic Effect



Top face:  
Stress-free boundary

$$[-p\mathbf{I} + \mathbf{K}]\mathbf{n} = -f_0\mathbf{n}$$

- $\mathbf{u}$  – velocity field
- $\rho$  – density of fluid (melt-pool)
- $p$  – fluid pressure
- $\mathbf{I}$  – identity tensor
- $\mu$  – fluid dynamic viscosity
- $\mathbf{F}$  – force in the fluid

Side & bottom faces:  
Wall BC

$$\mathbf{u} = \mathbf{0}$$





# Melt-Pool Churning Using A Coil: Key Properties & Inputs

Property	Variable	Value	Unit
<input checked="" type="checkbox"/> Dynamic viscosity	mu	1.4[mPa...	Pa·s
<input checked="" type="checkbox"/> Density	rho	2400	kg/m <sup>3</sup>
<input checked="" type="checkbox"/> Electrical conductivity	sigma...	4E6	S/m
<input checked="" type="checkbox"/> Relative permeability	mur_is...	1	1

Liquid Aluminum

<input checked="" type="checkbox"/> Electrical conductivity	sigma...	14.6E6	S/m
<input checked="" type="checkbox"/> Relative permeability	mur_is...	1	1

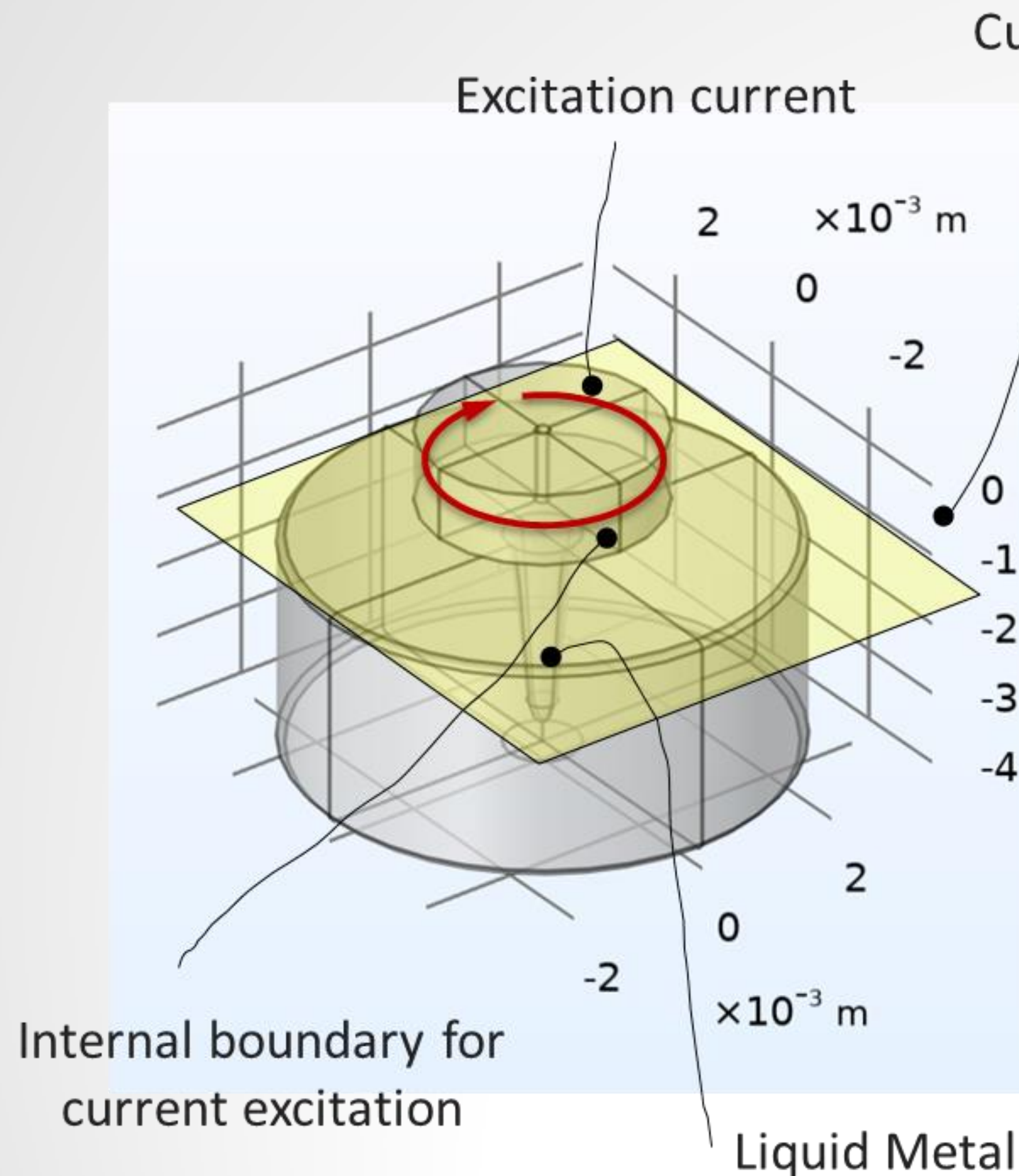
Solid Aluminum

Input/Property	Value
Coil excitation	Homogenous multiturn coil, 10 turns, 100[A]
Frequency	100 [Hz]
Permanent magnets	Remnant DC field, 1 [T]
Simulation study step	Time-Dependent
Duration	0.01[s]

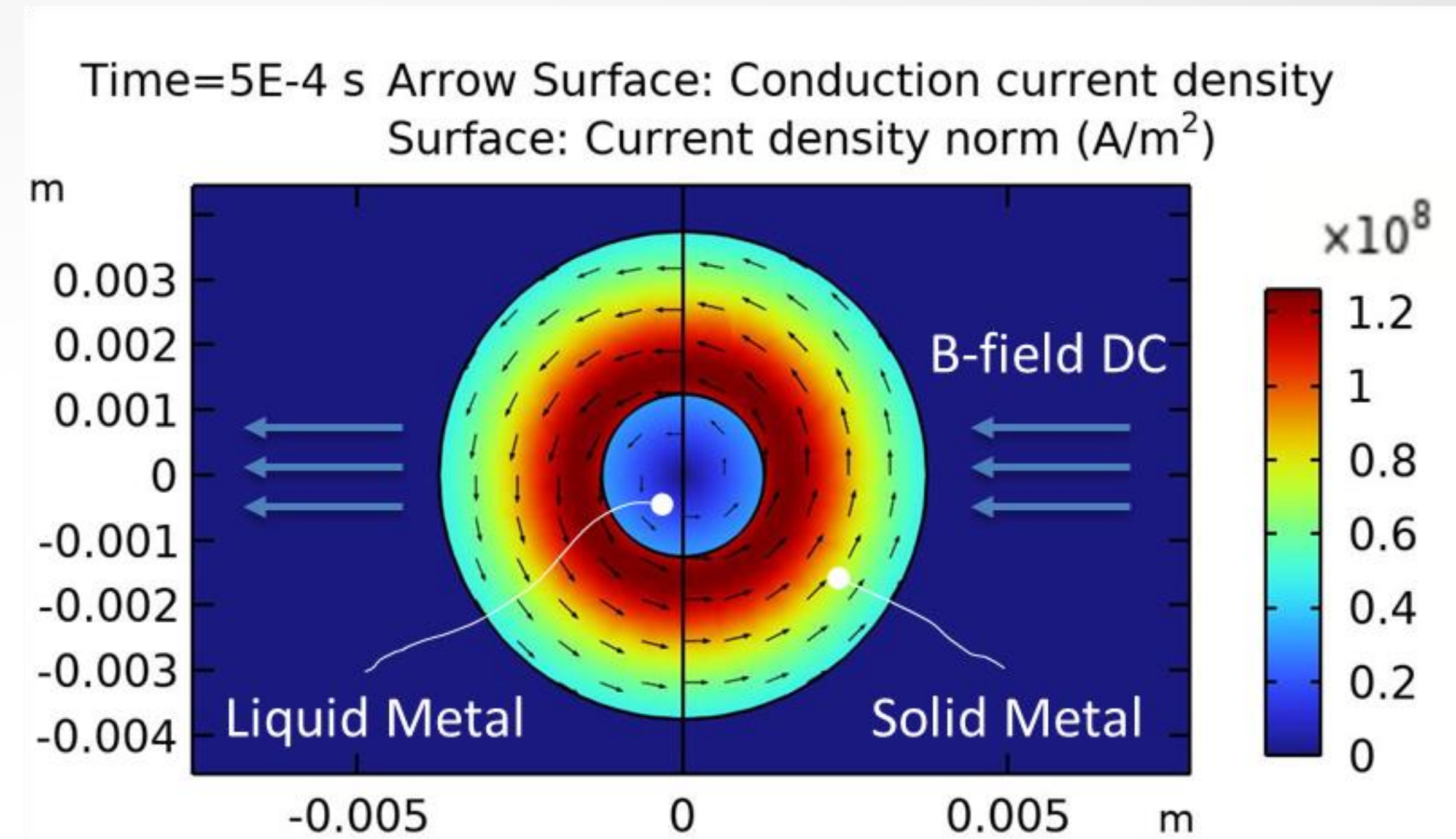
Model configuration



# Melt-Pool Churning Using A Coil: Excitation & Eddy Currents



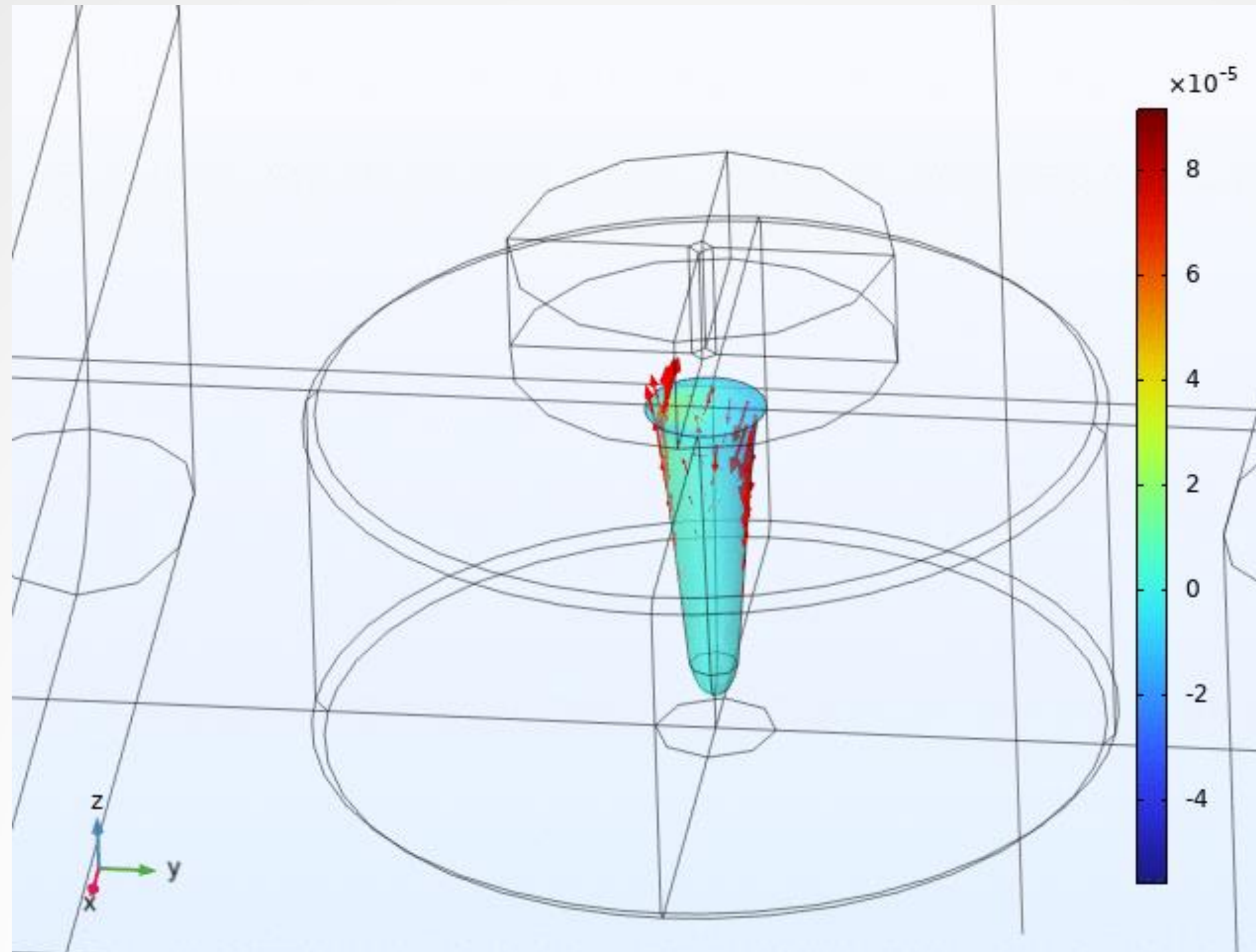
Cut plane for the eddy current plot



Eddy current distribution in the solid & liquid metal domains (XY-cut plane (red), 1.5mm under the top surface)



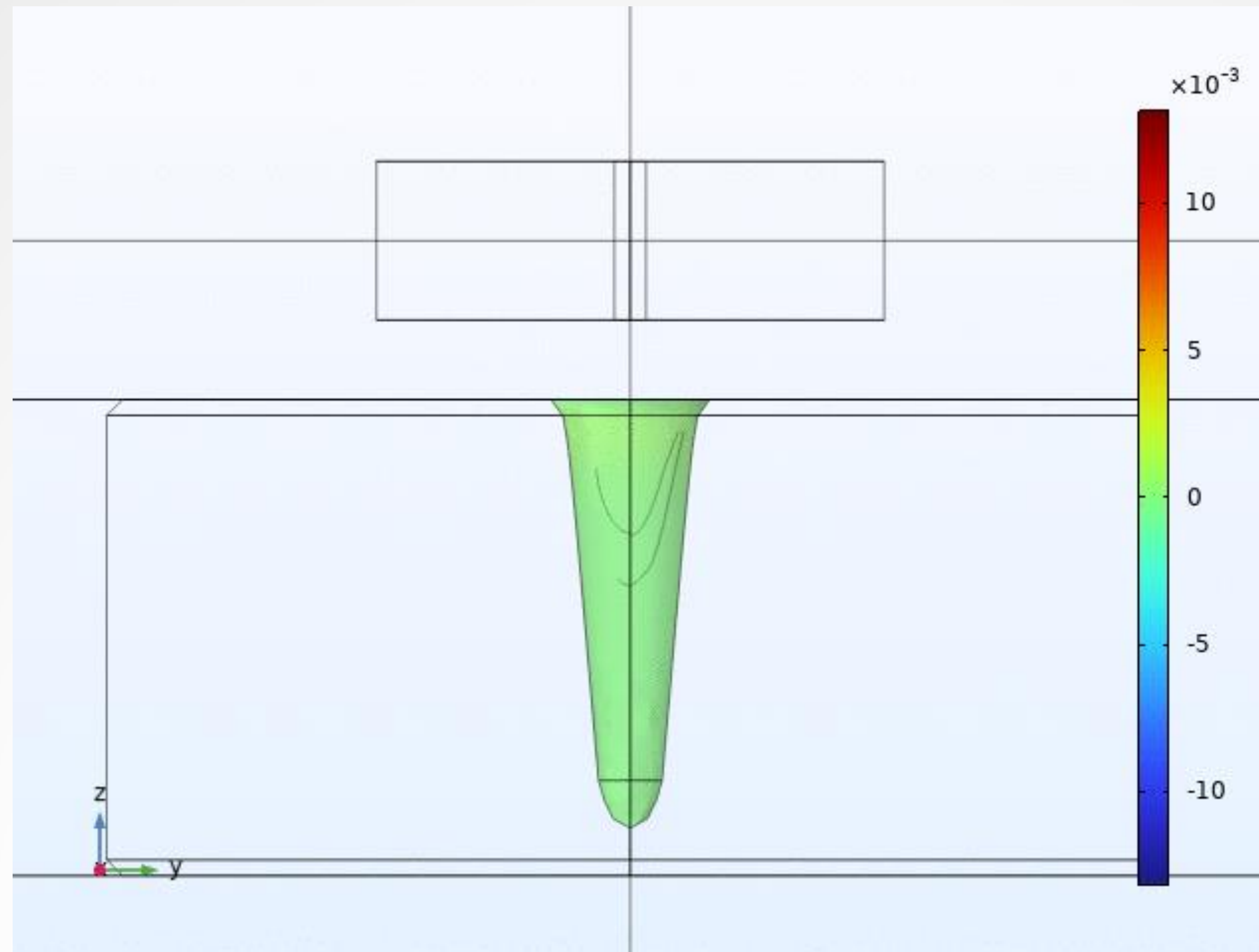
# Melt-Pool Churning Using A Coil: Melt-Pool Velocity Field



Velocity field of the melt-pool over one cycle of 100 Hz excitation



# Melt-Pool Churning Using A Coil: Particle Trajectory Tracing



Particle trajectories in the melt-pool (motion is exaggerated)



# Melt-Pool Churning Using A Coil: Field Excitation Apparatus at CVRC



Setup for magnetic field excitation and melt-pool churning



- Additive Manufacturing Melt-Pool Dynamics is a complex, coupled multi-physics process
- Preliminary studies indicate that it may be possible to use electromagnetic methods to churn the melt-pool



- Simulation of Mass Transfer Process (Navier-Stokes Equation) and Heat Energy Diffusion Process need to be completed
- Realistic melt-pool dimensions need to be simulated
- Modeling the process becomes even more complicated due to the differing time constants of the processes involved
- Calculation of melt-pool velocity should help determine the optimal electromagnetic excitation frequency
- Experimental validation necessary to establish the value of the approach in minimizing keyholes and porosity



# Questions & Answers

LAB TO LOGISTICS

Thank you!

