LAB TO LOGISTICS

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

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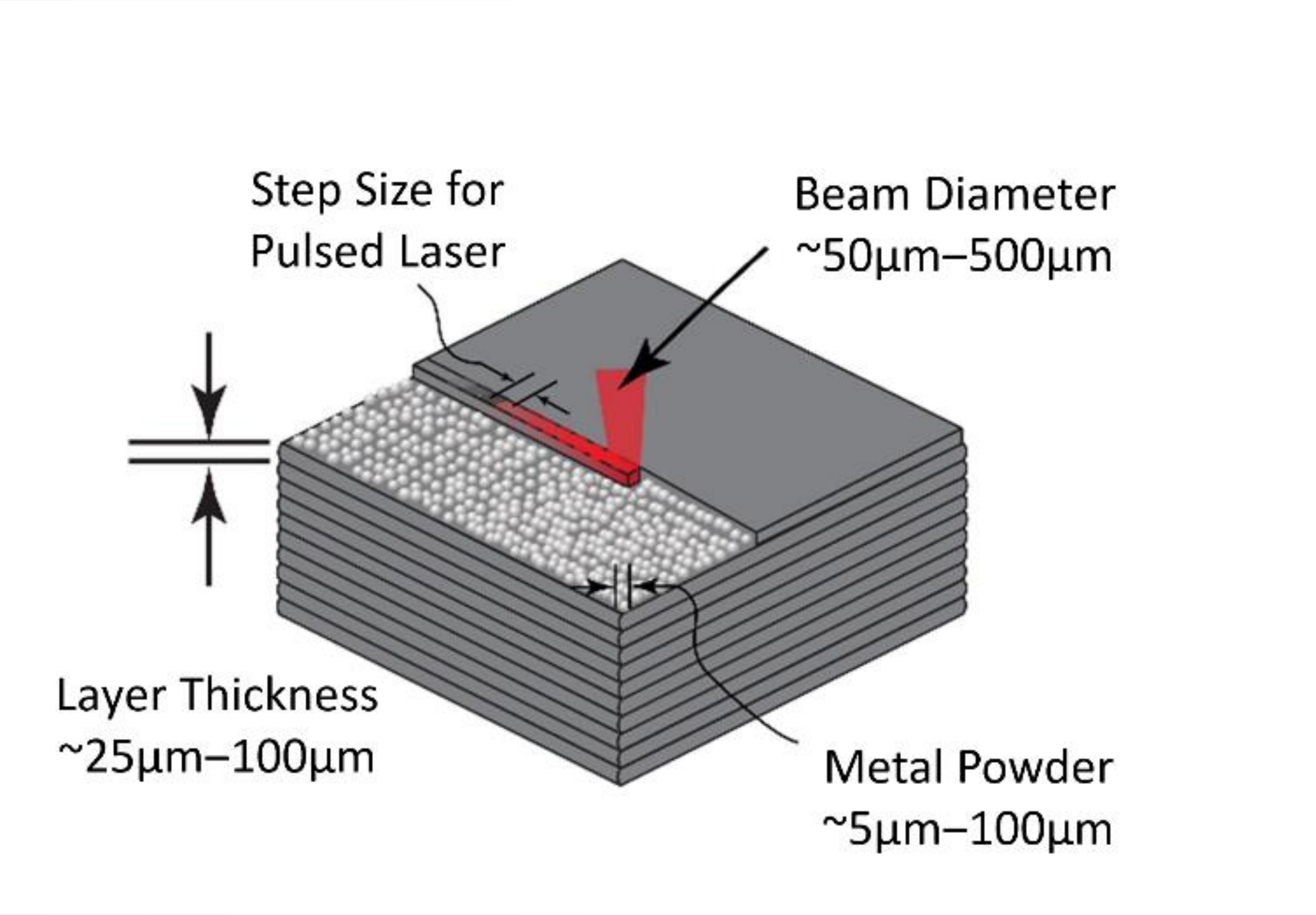
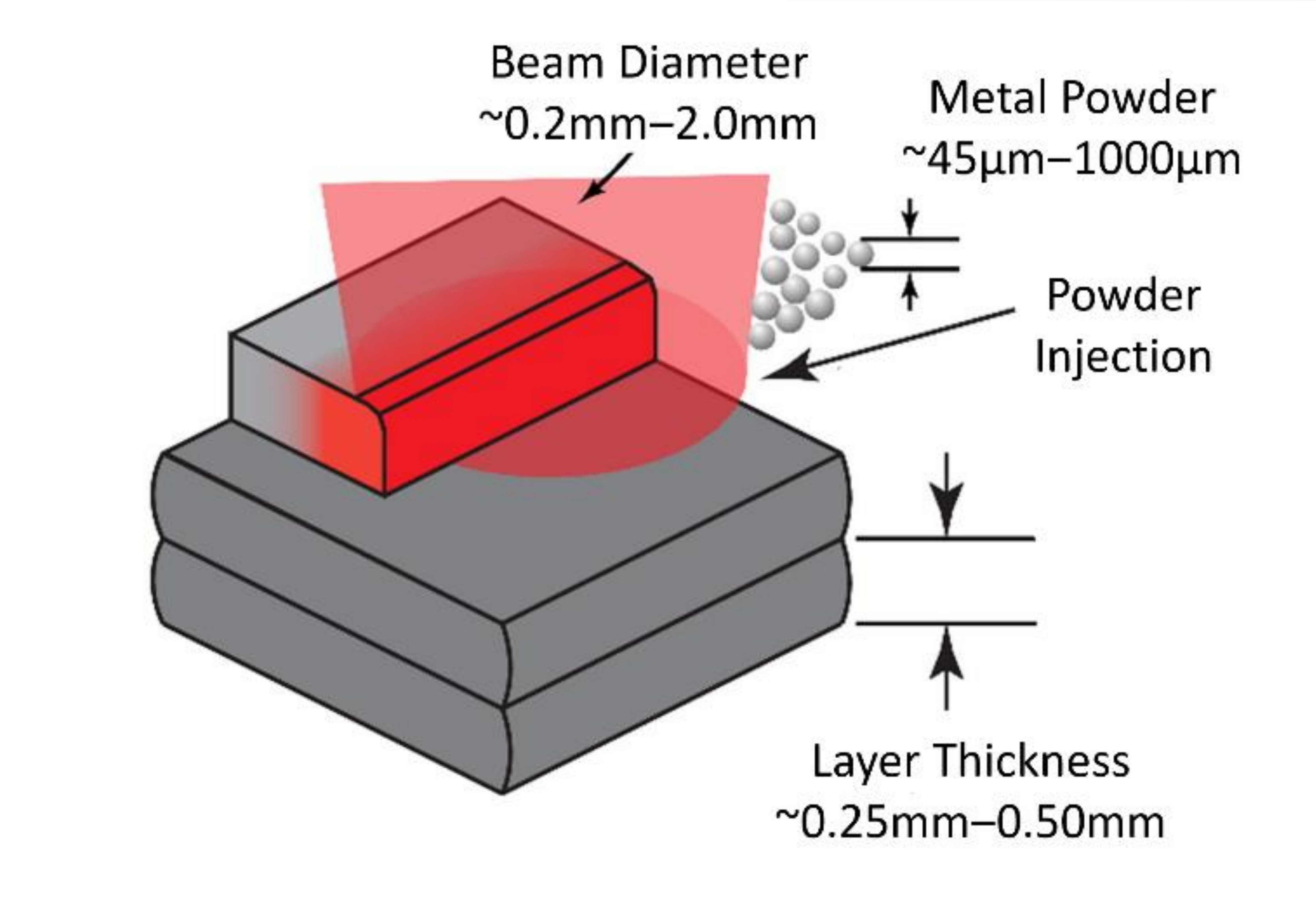
Metal Additive Manufacturing (MAM) in U.S. Army

- 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

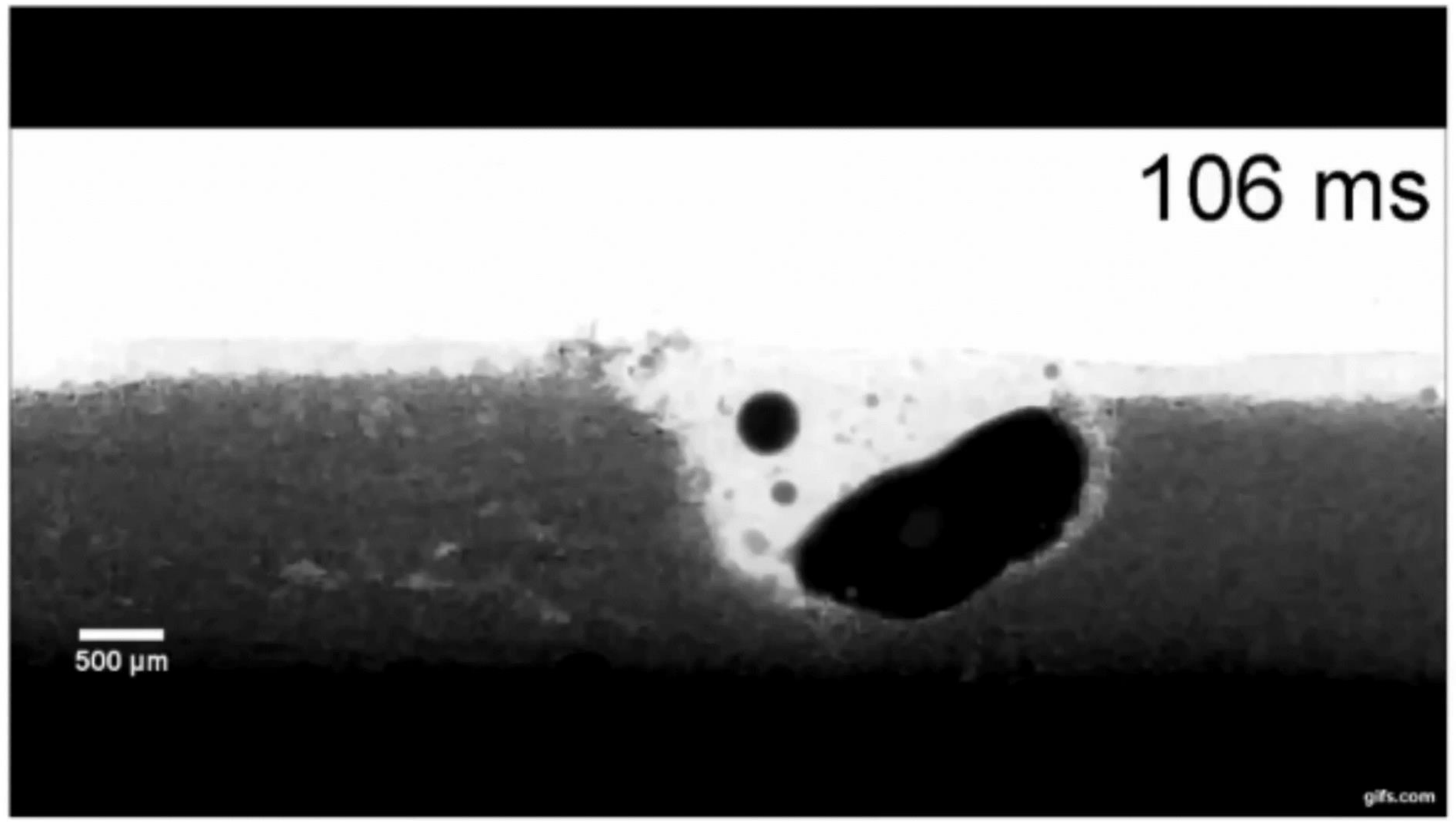




Powder Bed Fusion,
Selective Laser Melting, Direct Metal Laser Sintering

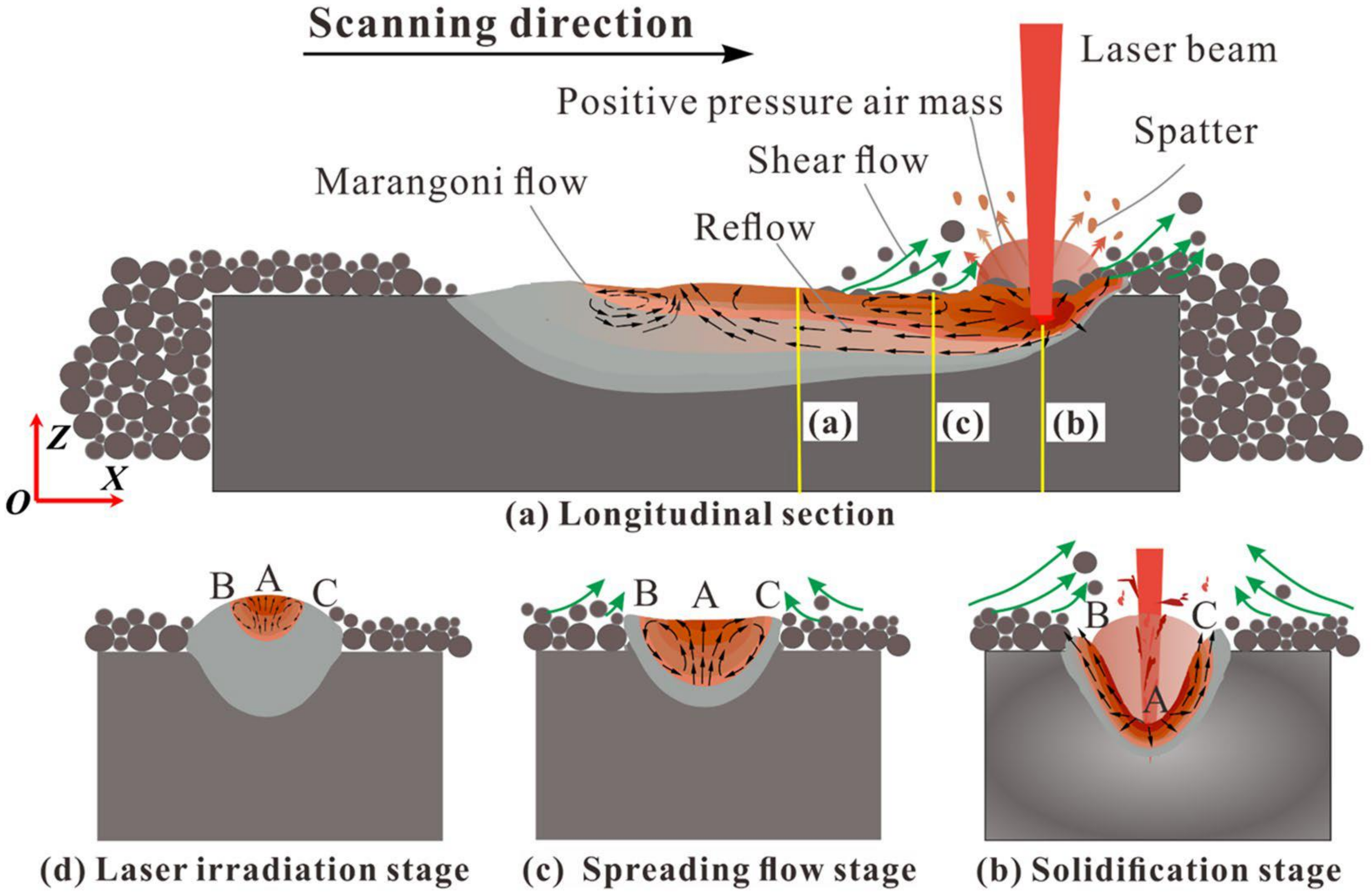
Direct Energy Deposition

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 (~50µm – 3mm)
- Caused by insufficient hatch spacing & irregular evolution of melt pool during solidification

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

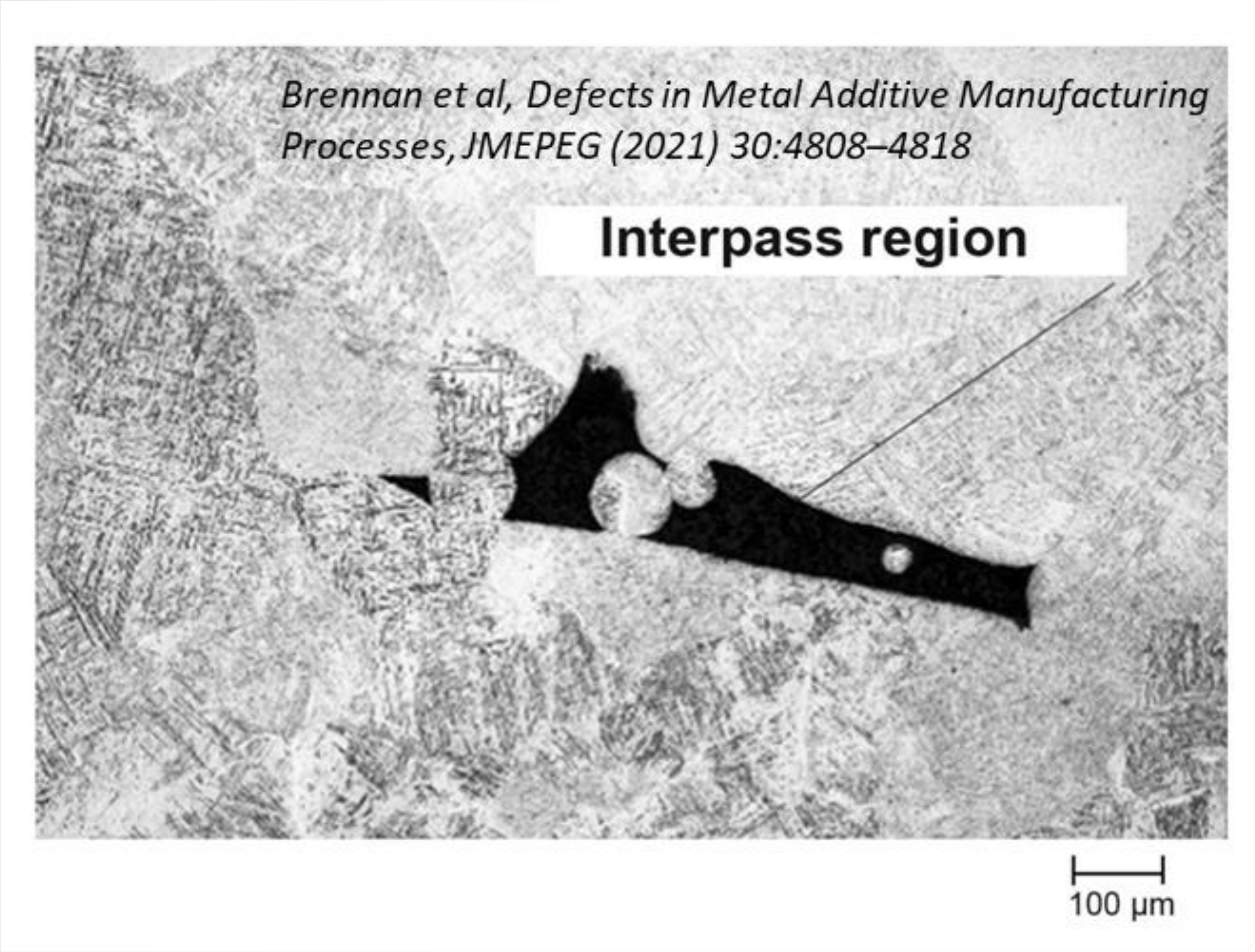
GAS POROSITY
- Spherical pores (~5µm – 50µm)
- Caused by gas entrapment, supersaturation of dissolved gases, and chemical reactions within the melt pool

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

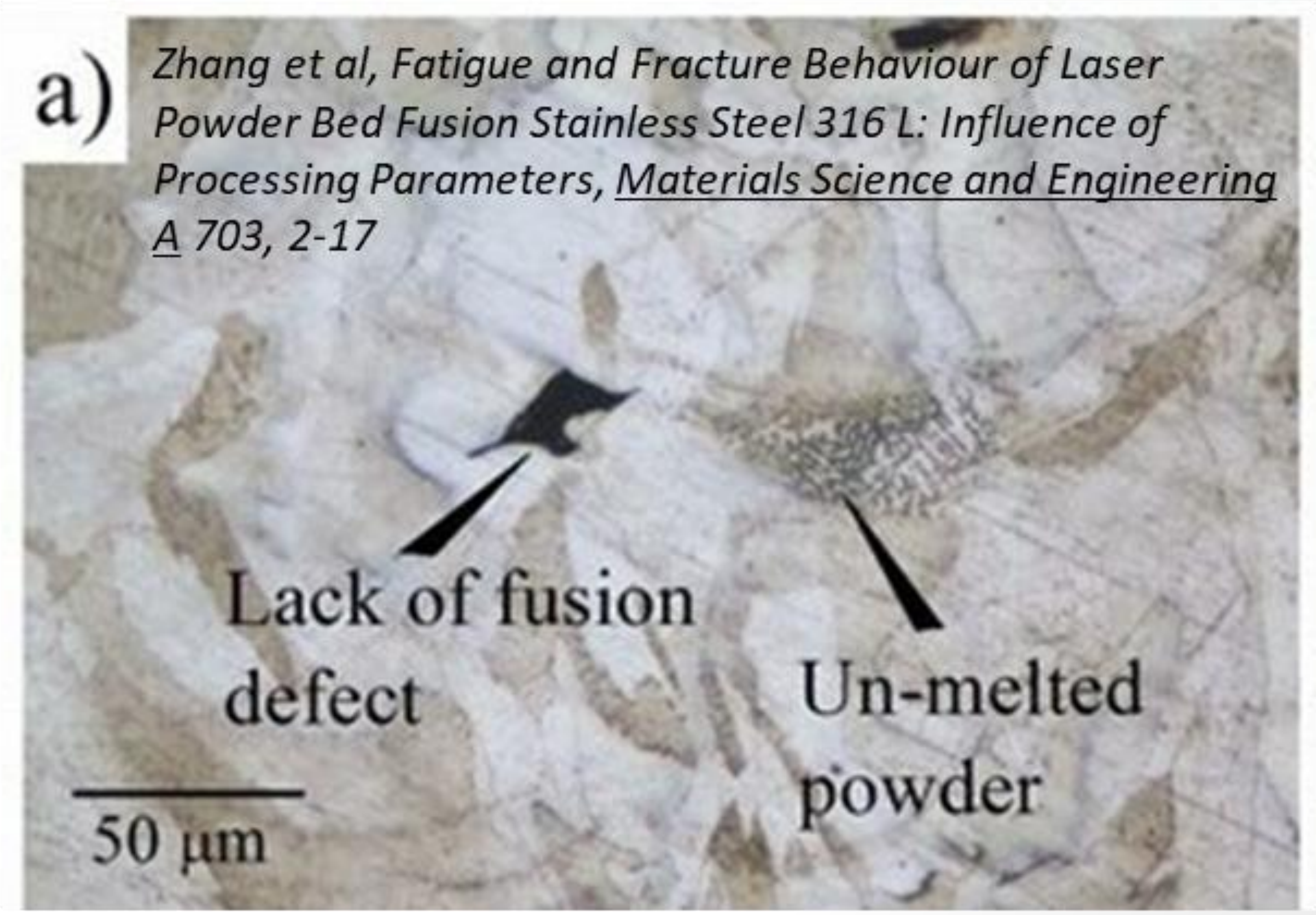
IMPURITIES
- Excess insoluble elements, such as carbon, oxygen, nitrogen, hydrogen & chlorine
- Introduced when producing & AM processing of metal powder

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

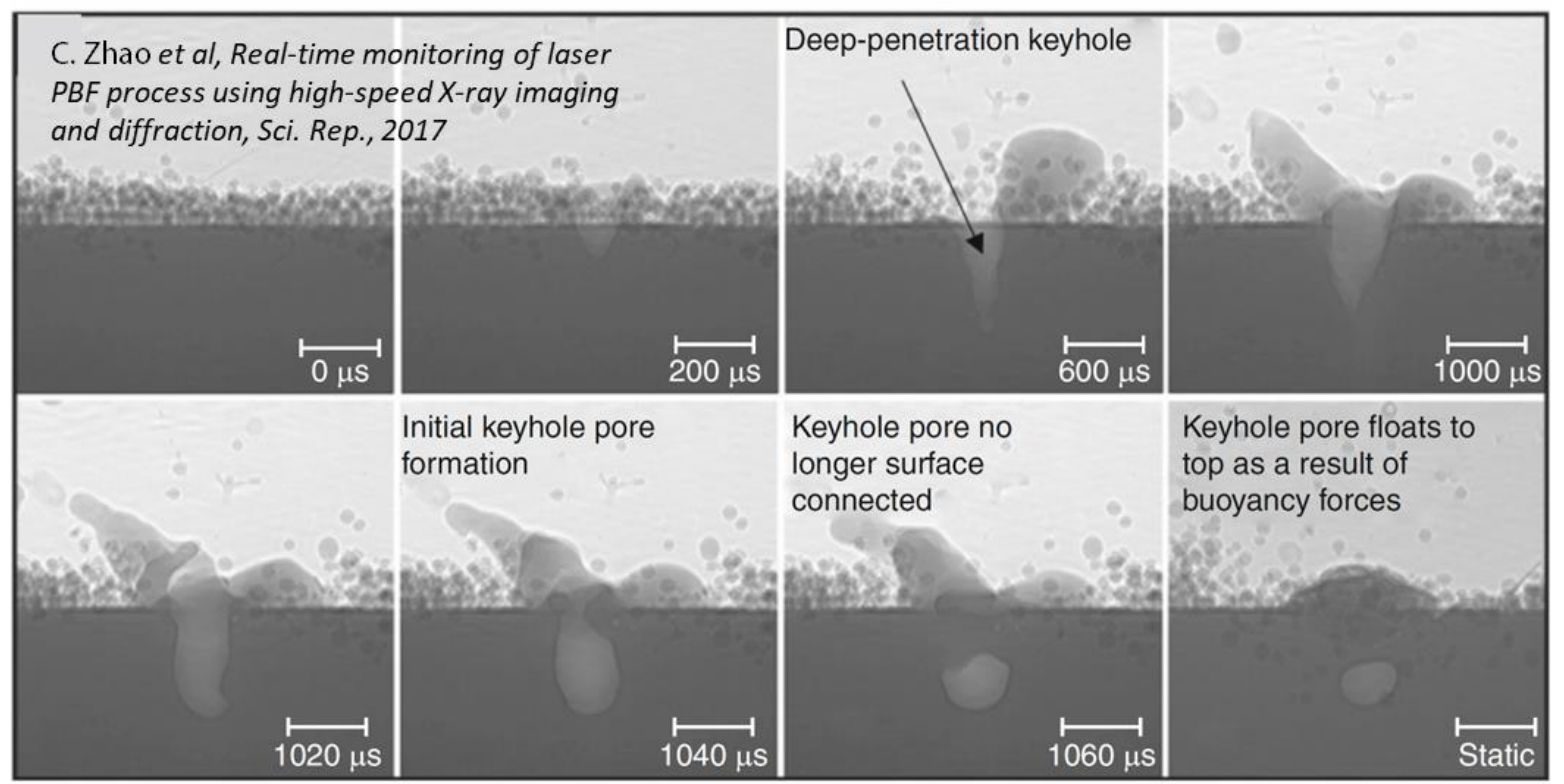


Lack-of-fusion defect formed in a DED-processed Ti-6Al-4V component



Lack of fusion in PBF-processed Stainless Steel 316L

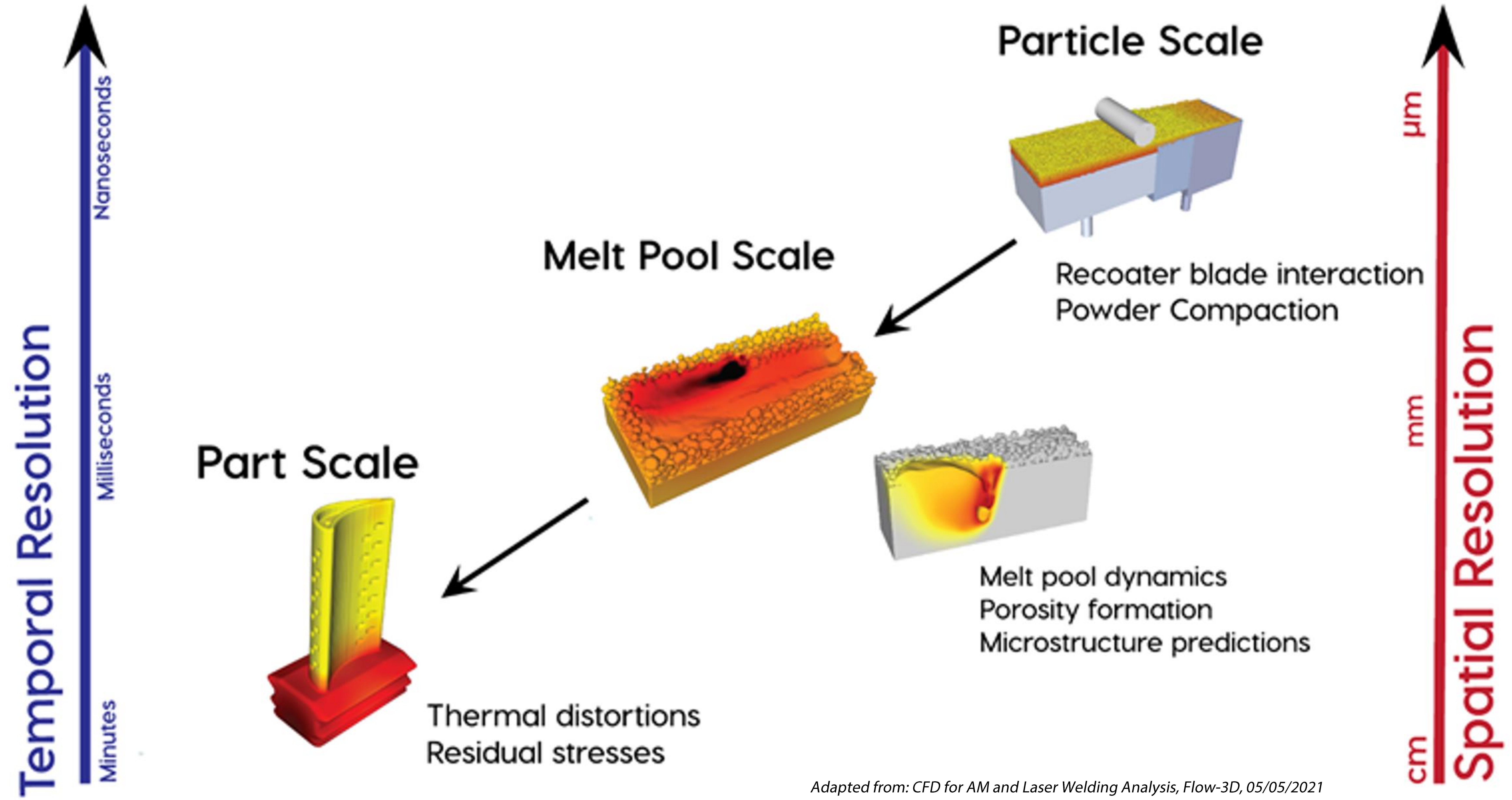
Common Defects in MAM: Keyholes



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

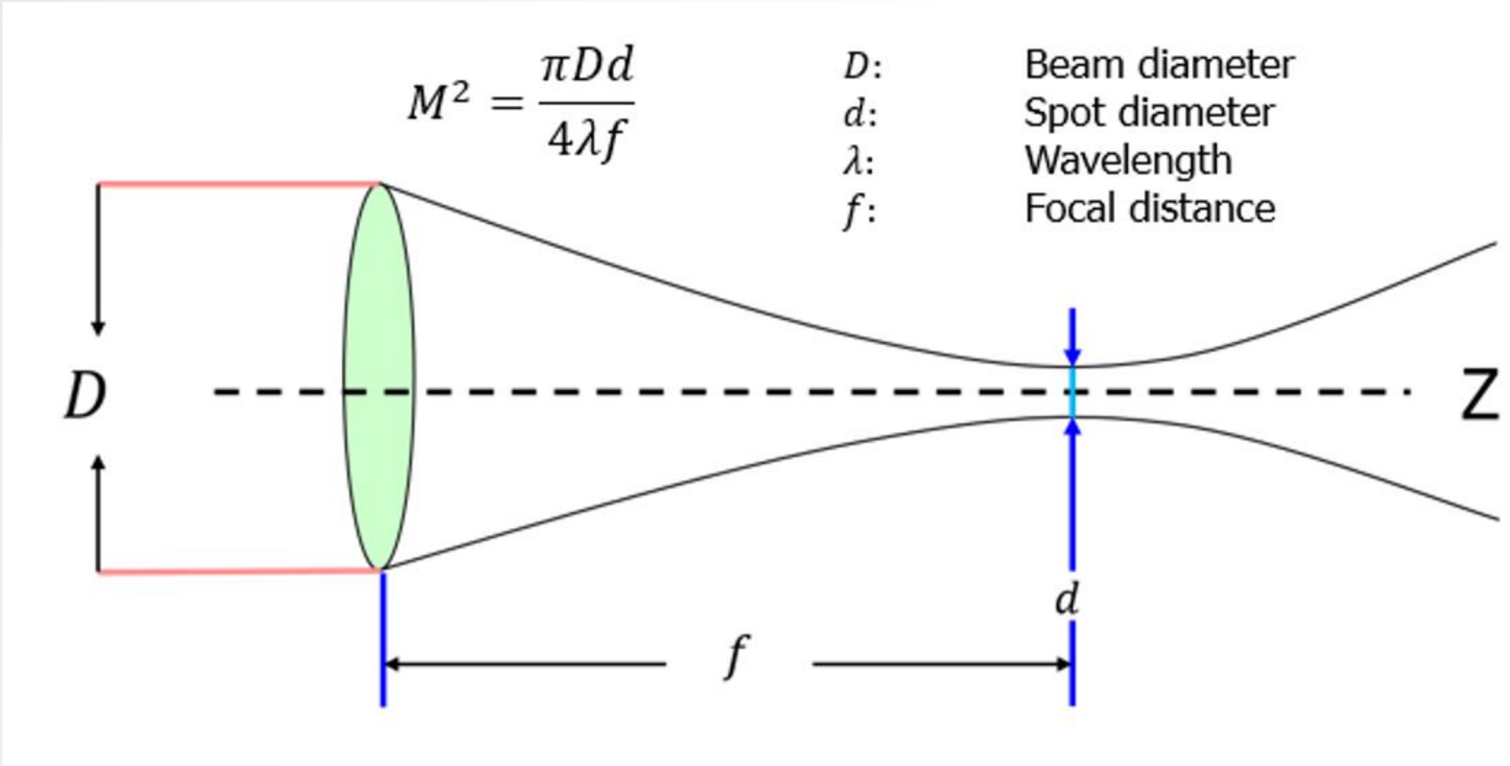
- A keyhole is formed upon increasing the laser power above the optimal value

MAM: Multiphysics Modeling & Different Time/Size Scales

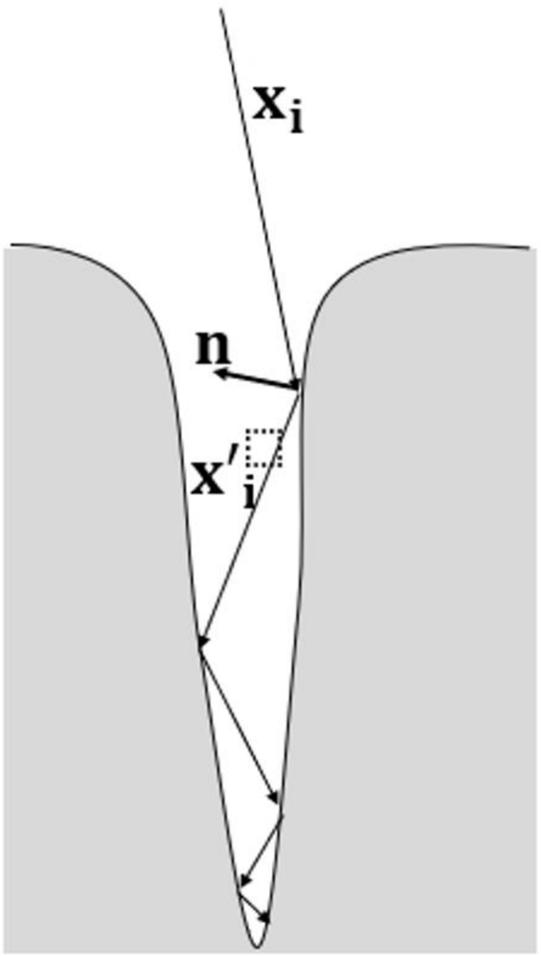


Adapted from: CFD for AM and Laser Welding Analysis, Flow-3D, 05/05/2021

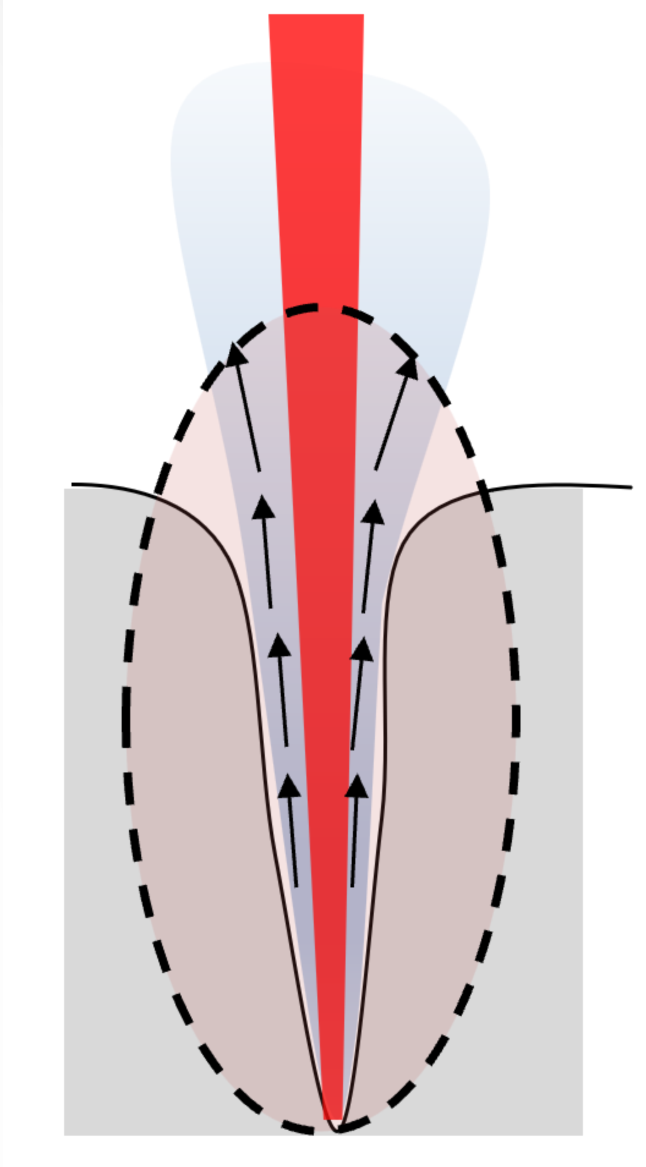
MAM: Laser Heat Source Interaction with Metal



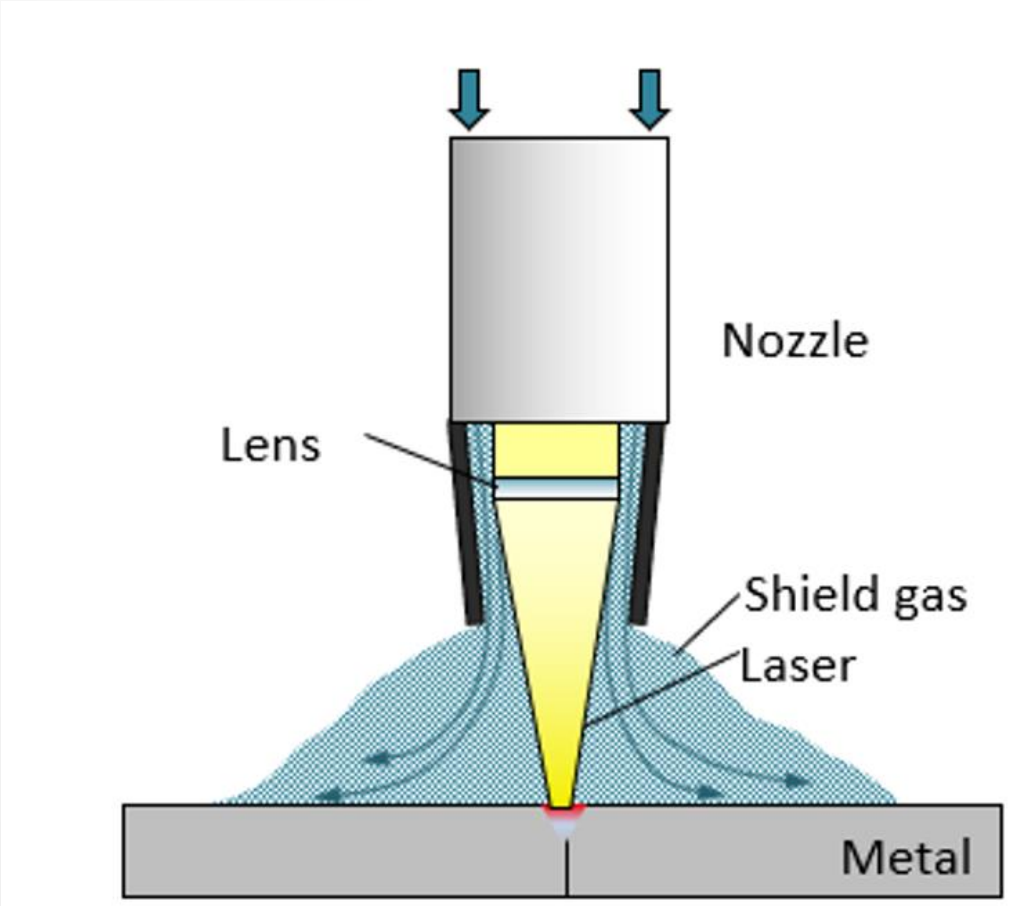
Laser heat flux profile



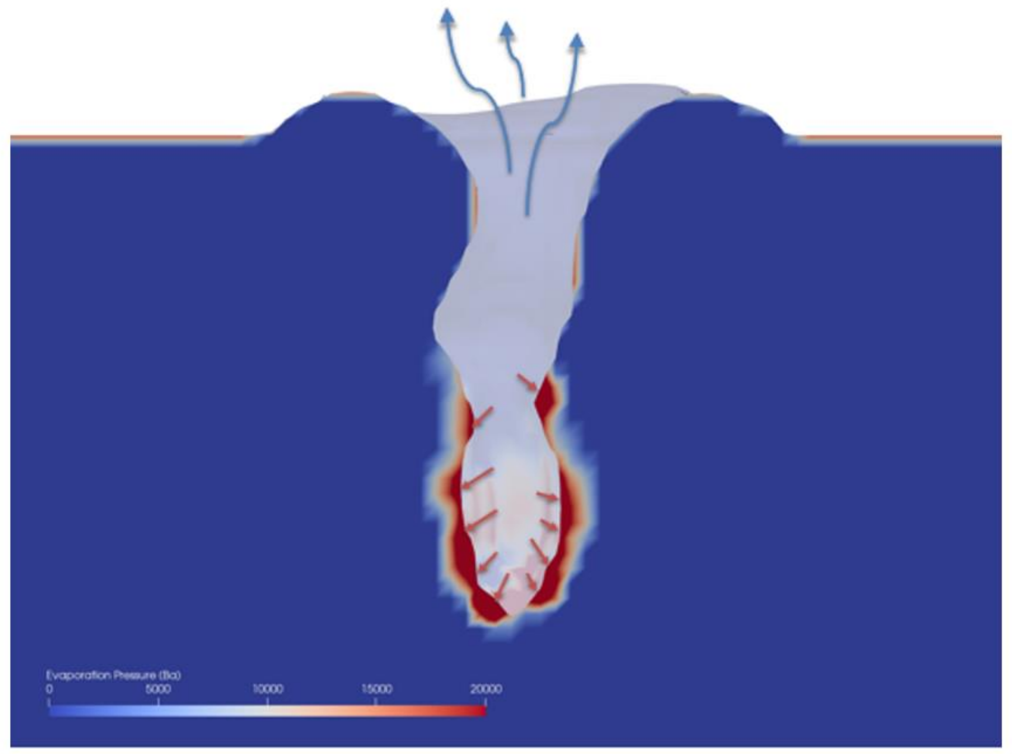
Laser beam reflections



Plume dynamics

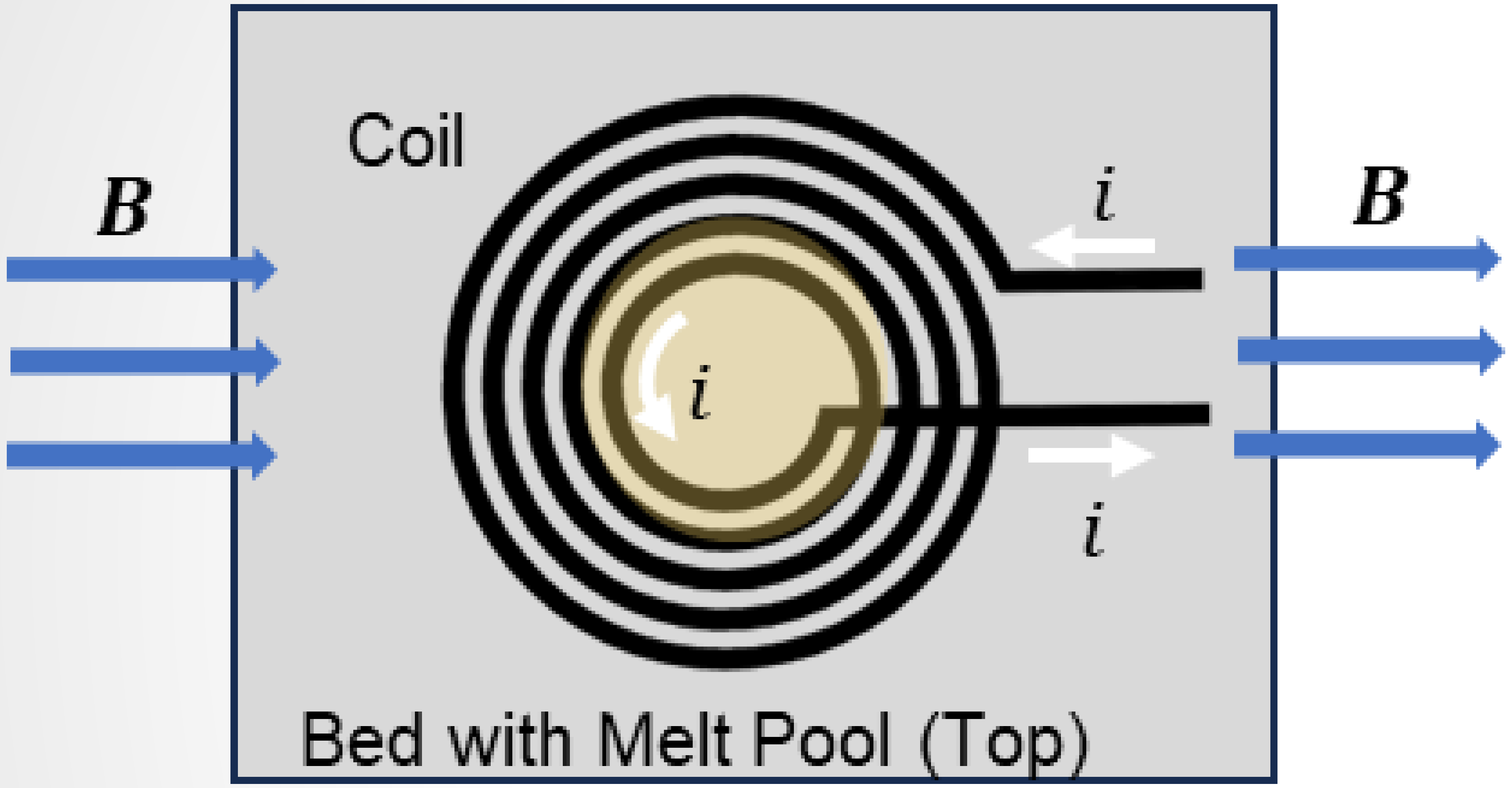


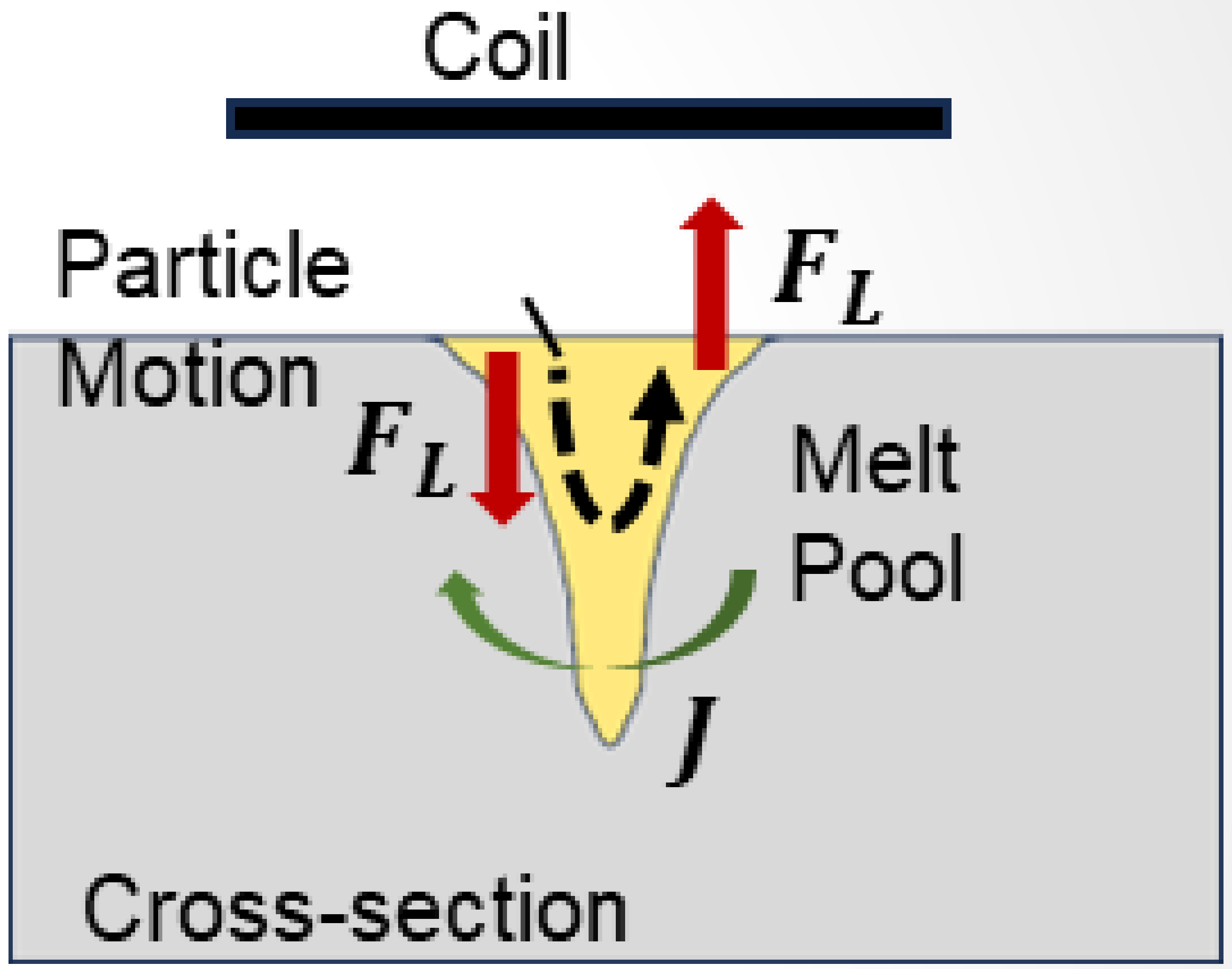
Shield gas pressure



Evaporation pressure

Electromagnetic Control of Melt-Pool





<u>Coil & permanent magnets for melt-pool churning</u>

Lorentz force: F = J×B

Melt-Pool Churning: Multiphysics Computational Methods

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EM Fields

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}$$
$$\mathbf{B} = \nabla \times \mathbf{A}$$
$$\boldsymbol{J} = \sigma \boldsymbol{E} + \boldsymbol{J}_e$$
$$\boldsymbol{E} = -\frac{\partial A}{\partial t}$$
$$\boldsymbol{F} = \boldsymbol{J} \times \mathbf{B}$$
$$\boldsymbol{J} = \sigma(\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B})$$

Mass Transfer

$$\rho \nabla \cdot \boldsymbol{u} = 0$$
$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = \nabla \cdot \left(-p\boldsymbol{I} + (\mu + \mu_T)\left(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T\right)\right) + \rho \boldsymbol{g} + \boldsymbol{F}$$

Heat Transfer

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

Laser Energy Source

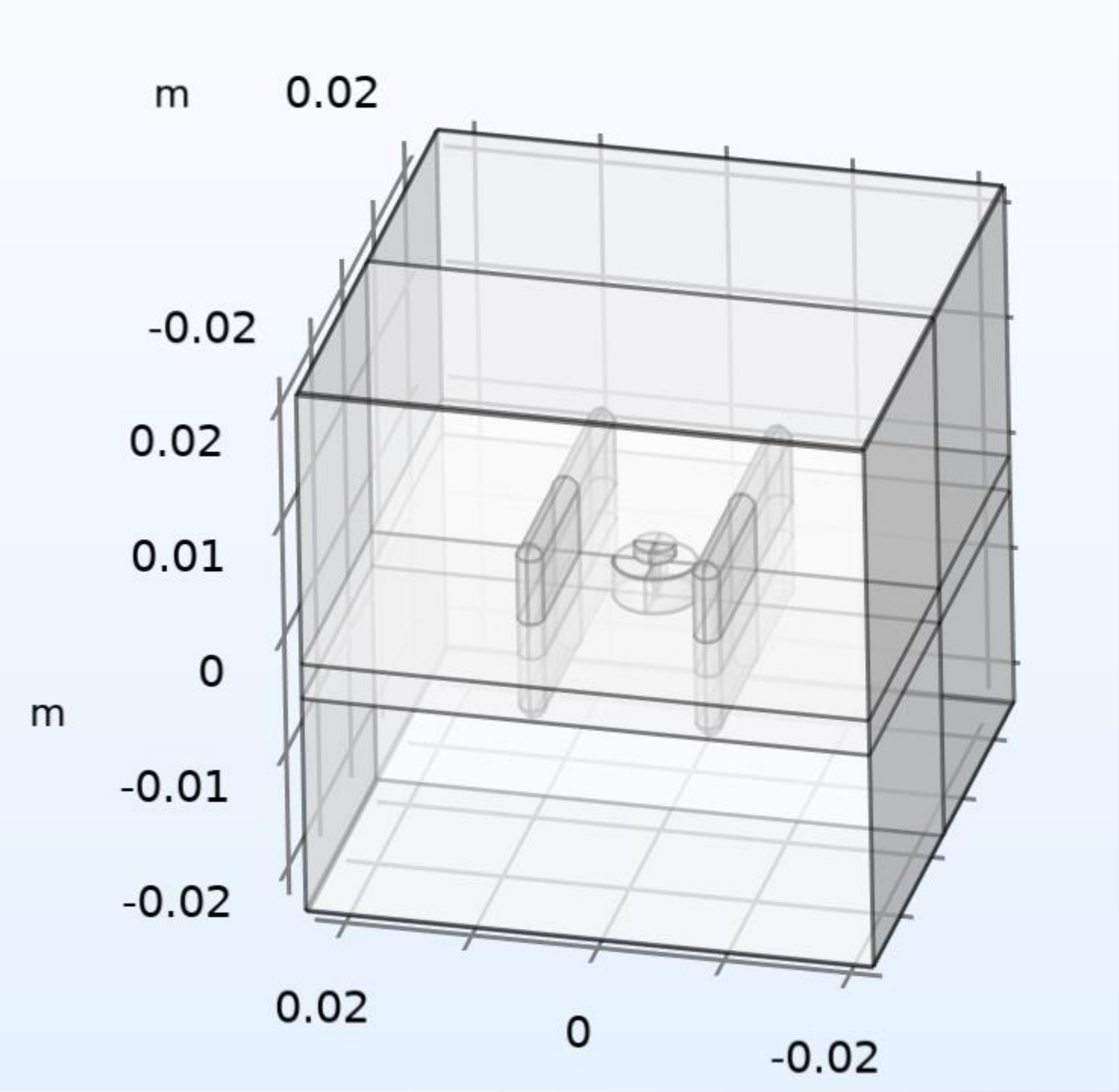
$$Q = \frac{2P\alpha}{\pi r_b^2}(1 - R)\exp\left(\frac{-2x^2}{r_b^2}\right)\exp(-\alpha z)$$

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

Melt-Pool Churning Using A Coil: FE Model Geometry

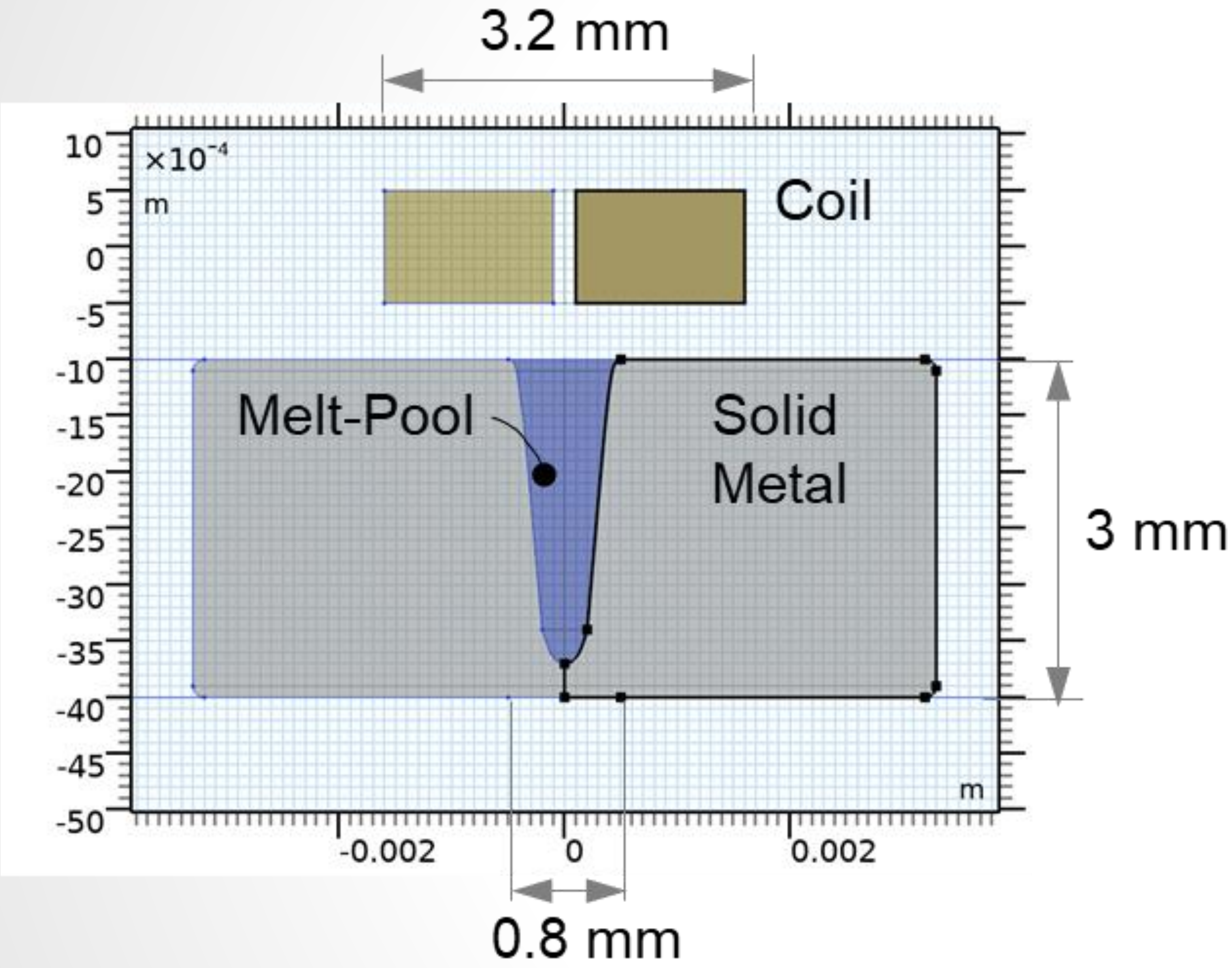
COMSOL Multiphysics 6.1:
- Magnetic Fields Interface
- Laminar/Turbulent Flow Interface
- Magnetohydrodynamics Effect

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

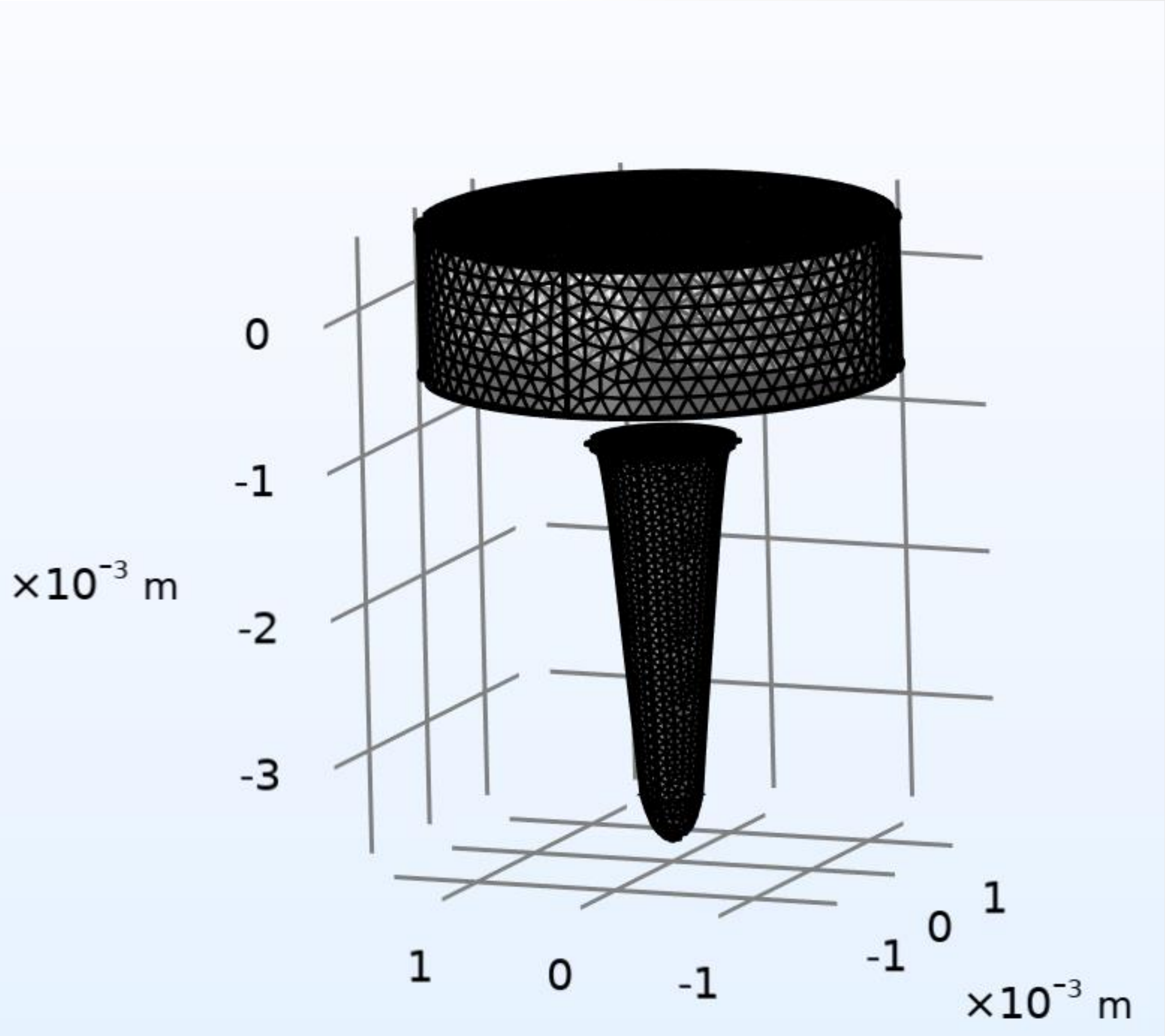


Overall FE model geometry

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

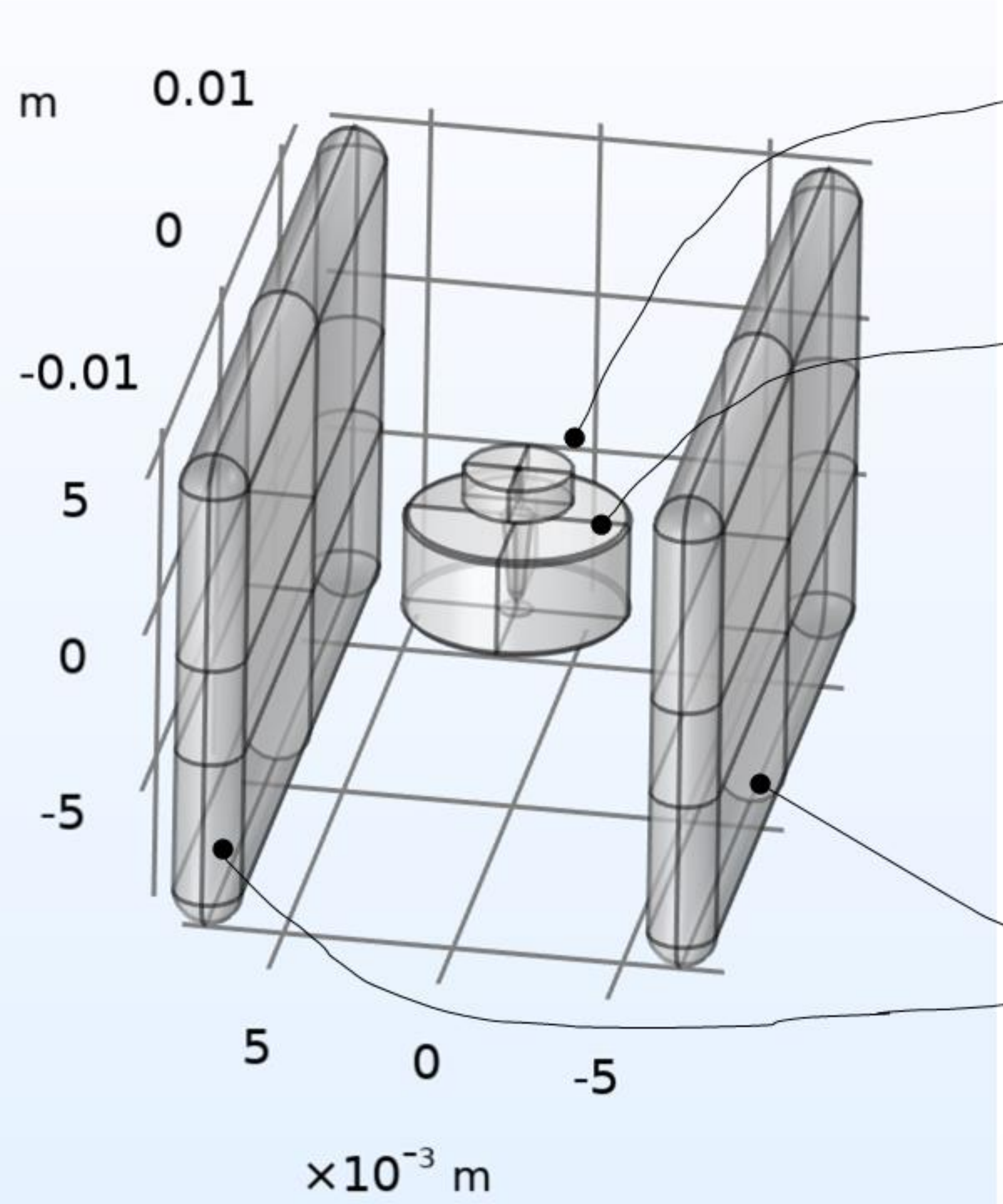
- Magnetic Fields *(mf)*
  - Ampère's Law 1
  - Magnetic Insulation 1
  - Initial Values 1
  - Coil 1
  - Ampère's Law 2
  - Edge Current 1

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

$$\mathbf{B} = \mu_0 \mu_{rec} \mathbf{H} + \mathbf{B}_r,$$
$$\mathbf{B}_r = \|\mathbf{B}_r\| \frac{\mathbf{e}}{\|\mathbf{e}\|} \quad 1\ [\mathrm{T}]$$

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

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

- Laminar Flow *(spf)*
  - Fluid Properties 1
  - Initial Values 1
  - Wall 1
  - Open Boundary 1

COMSOL Single Phase Flow

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

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

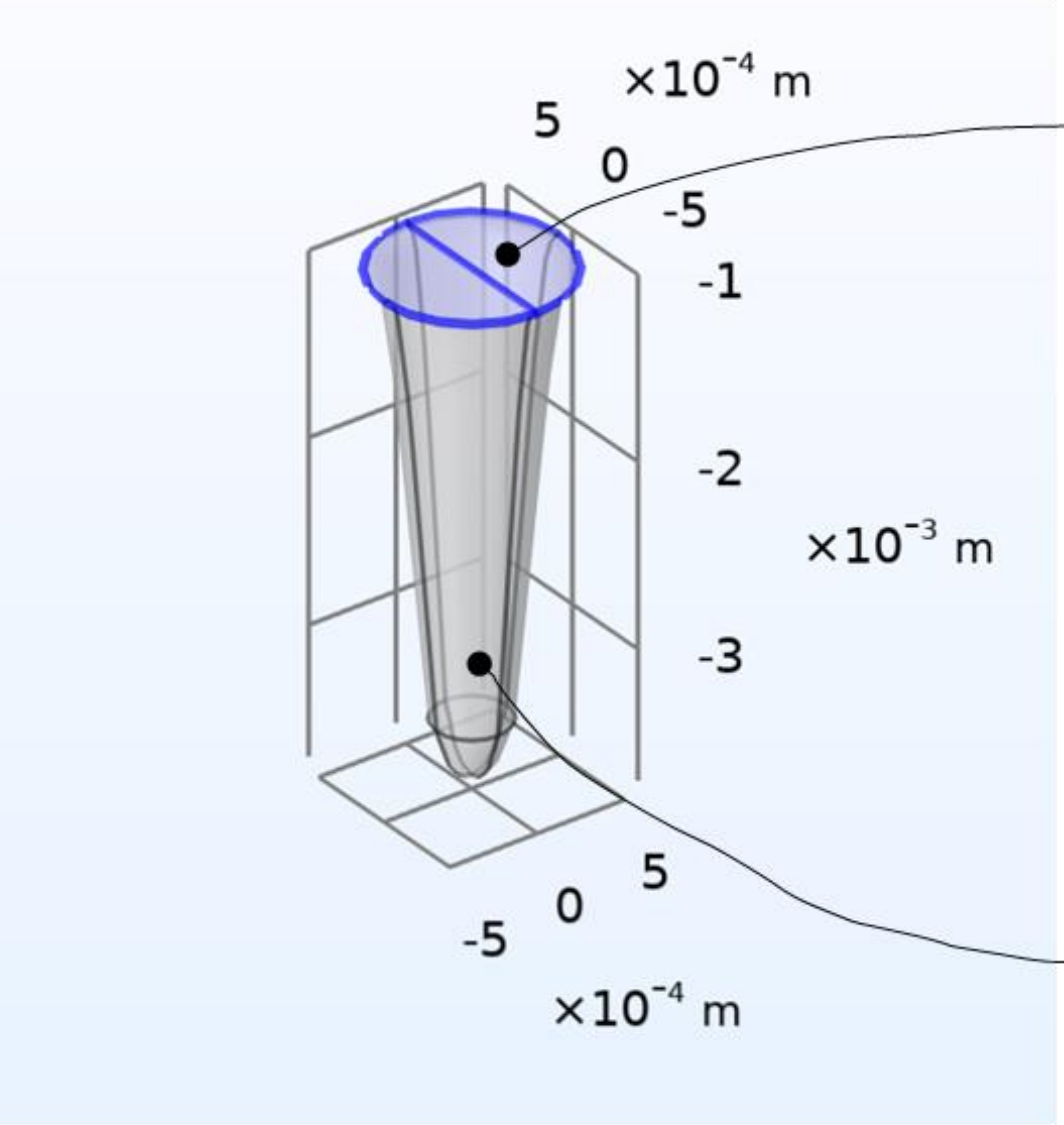
$$\mathbf{K} = \mu\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)$$

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

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

$\boldsymbol{u}$ – velocity field
ρ – density of fluid (melt-pool)
p – fluid pressure
$\boldsymbol{I}$ – identity tensor
μ – fluid dynamic viscosity
$\boldsymbol{F}$ – 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
☑	Dynamic viscosity	mu	1.4[mPa...	Pa·s
☑	Density	rho	2400	kg/m^3
☑	Electrical conductivity	sigma...	4E6	S/m
☑	Relative permeability	mur_is...	1	1

Liquid Aluminum

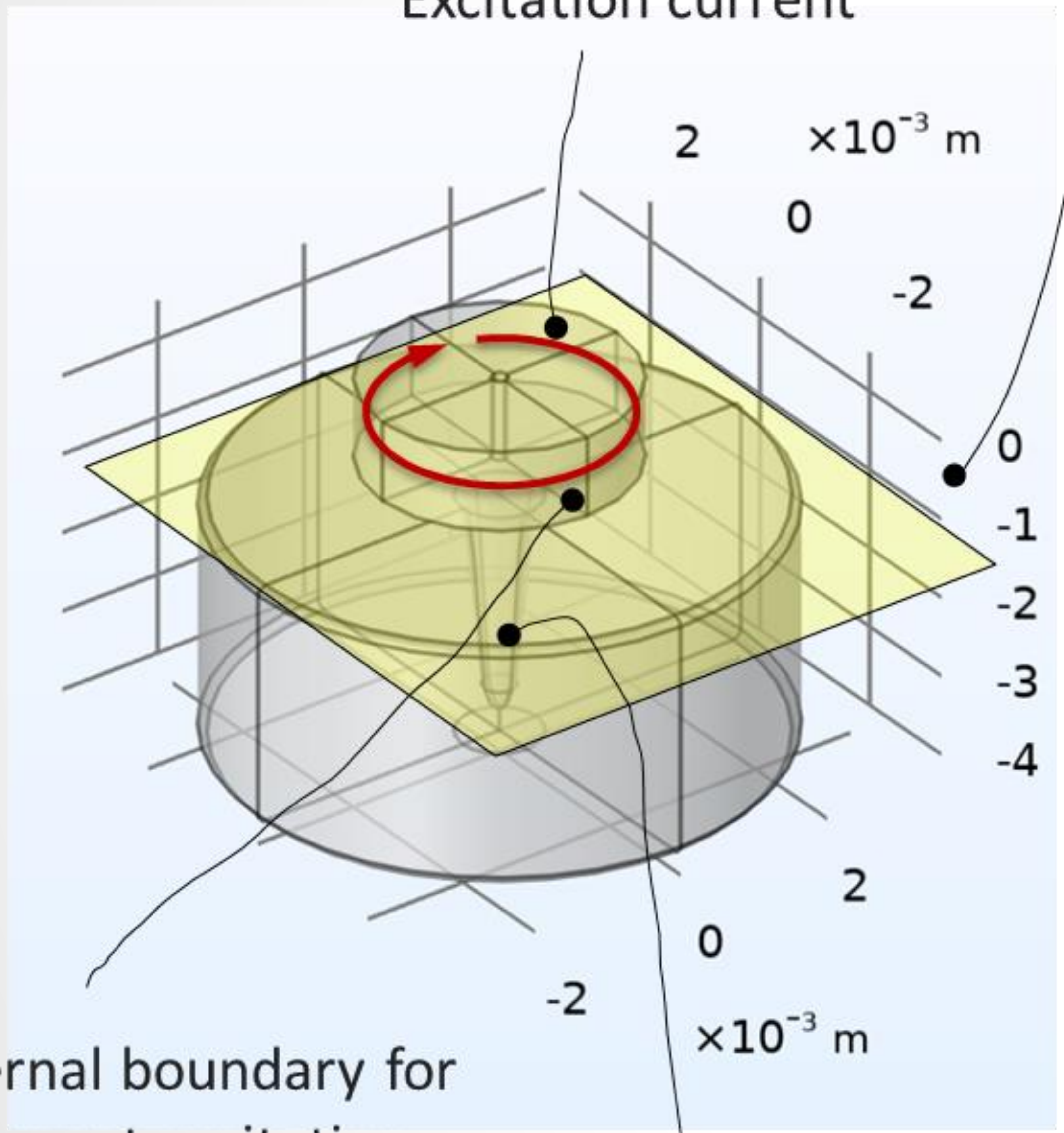
☑	Electrical conductivity	sigma...	14.6E6	S/m
☑	Relative permeability	mur_is...	1	1

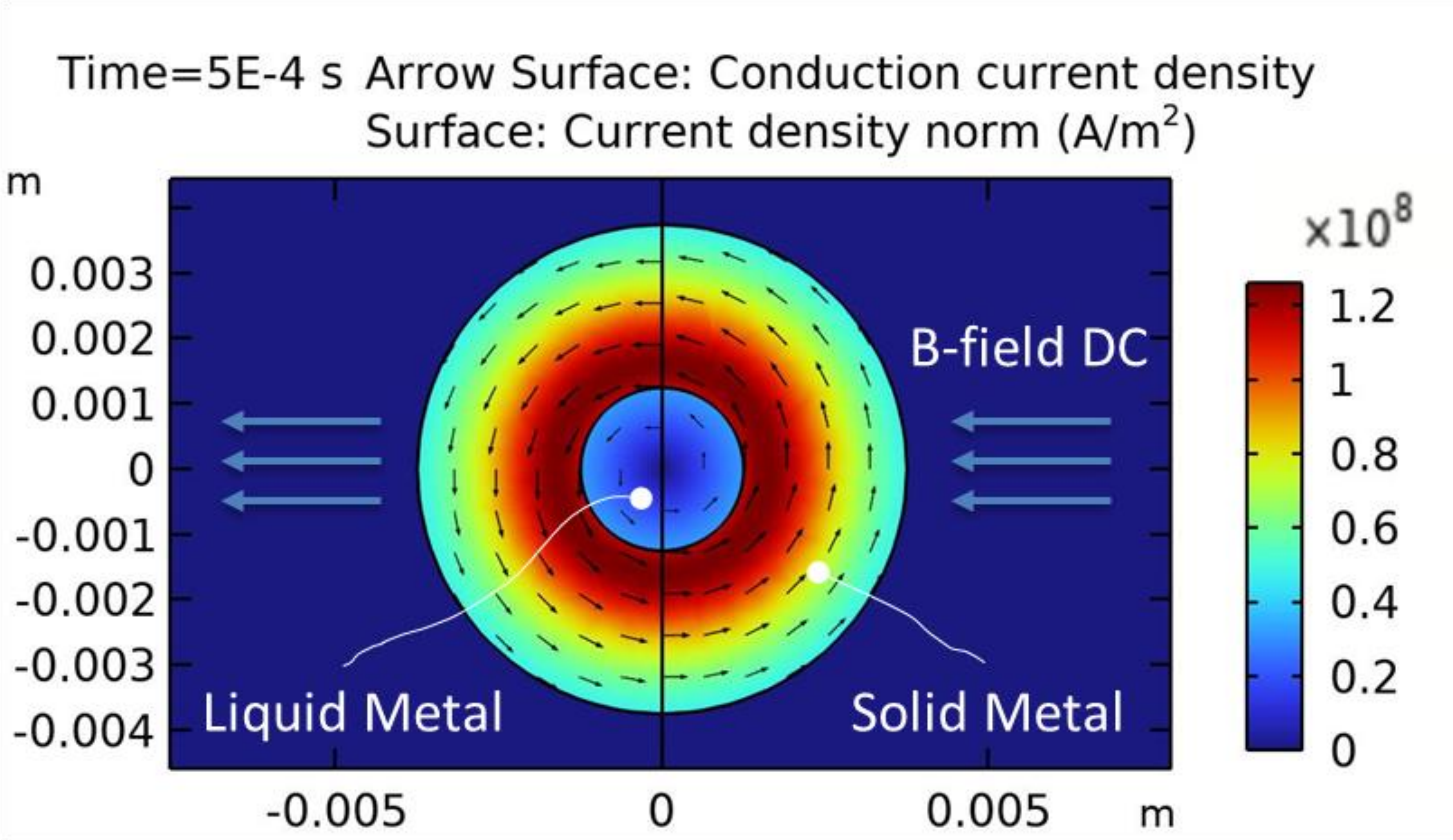
Solid Aluminum

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

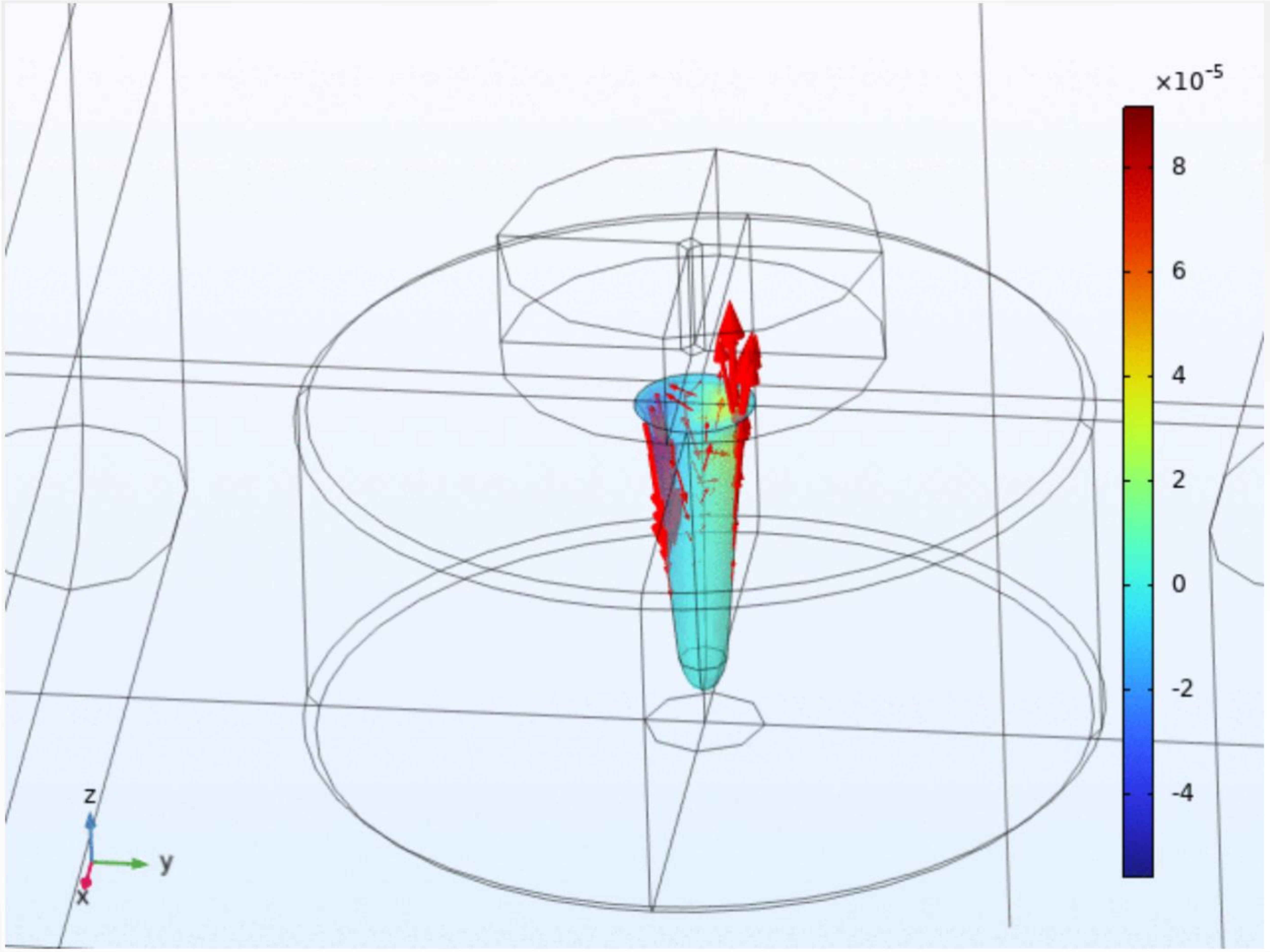
Melt-Pool Churning Using A Coil: Excitation & Eddy Currents





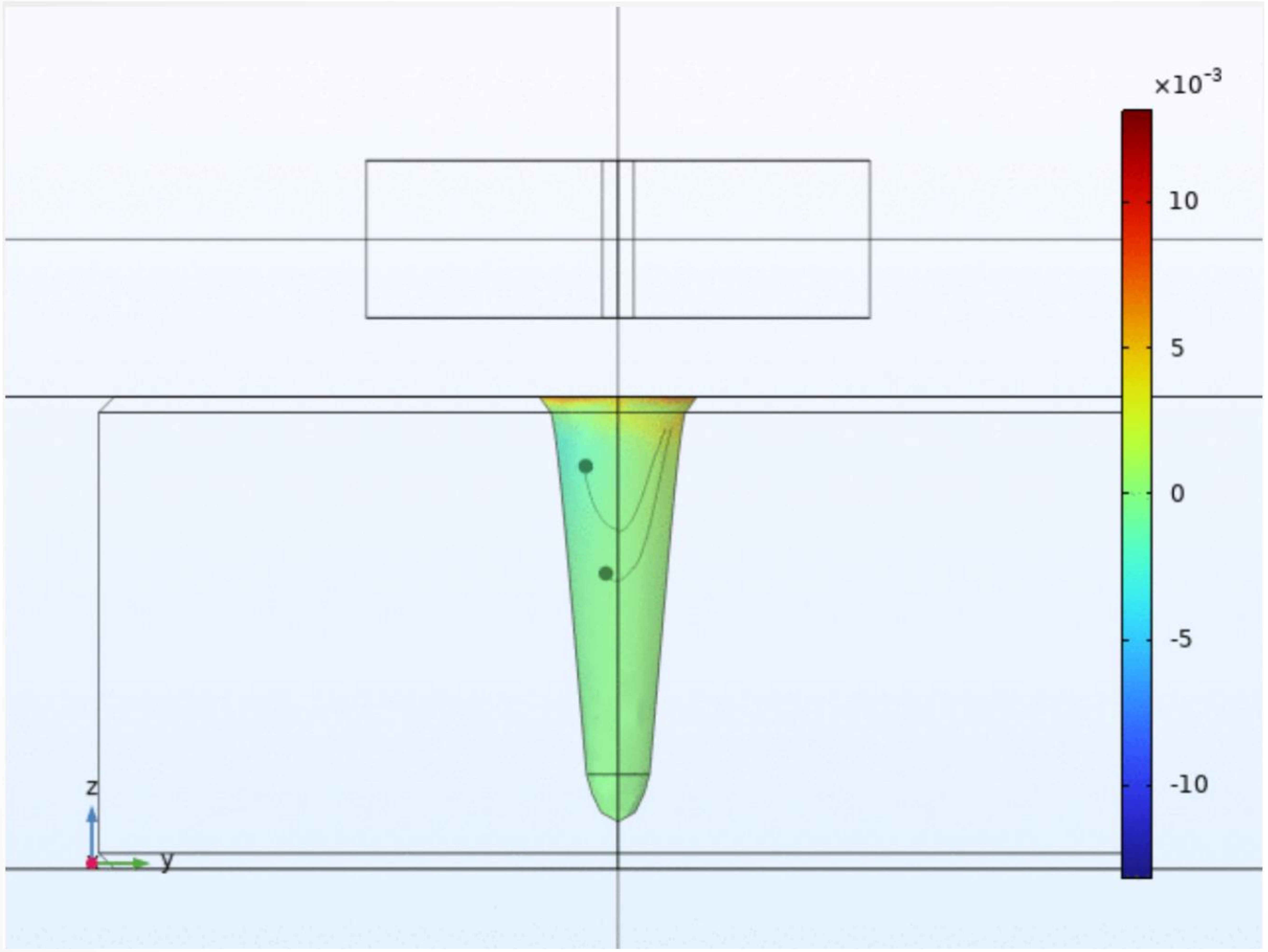
Eddy current distribution in the solid & liquid metal domains (XY-cut plane (red), 1.5mm under the top surface)

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

Conclusions

- 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

Future Work

- 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

Thank you!