Fast optimization of additively manufactured metallic parts with a combination of adaptive feedforward control and numerical simulation (SMARTAM)

Academic Partners:

- EPFL : L. Schlenger, J. Jhabvala, E. Boillat, R. Logé
- Empa : G. Masinelli, J. Yang, C. Leinenbach, K. Wasmer, P. Hoffmann
- PSI : S. Gaudez, S. Van Petegem
- ETHZ : S. Stanko, M. Stoica, J. F. Löffler

Industrial Partners:

PX Group, Heraeus Materials, Patek Philippe, Swatch Group

Overview - Motivation

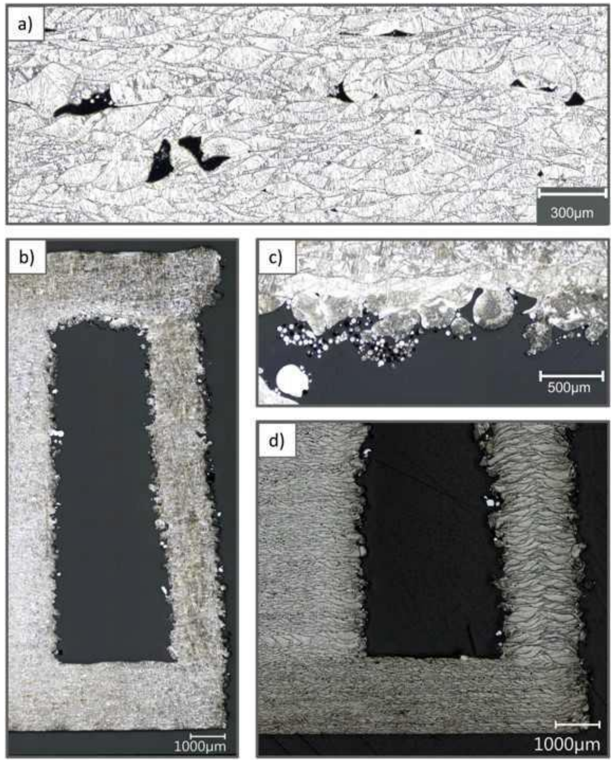
Laser Powder Bed Fusion (LPBF):

layer by layer deposition additive manufacturing technique

- Single sets of process parameters are defined for a given part despite its intricate geometry
- Heat flux influenced by geometrical features
  - Variations in melt pool geometry
  - Formation of defects
- Uncontrolled local thermal history → undesirable microstructures

REMEDY

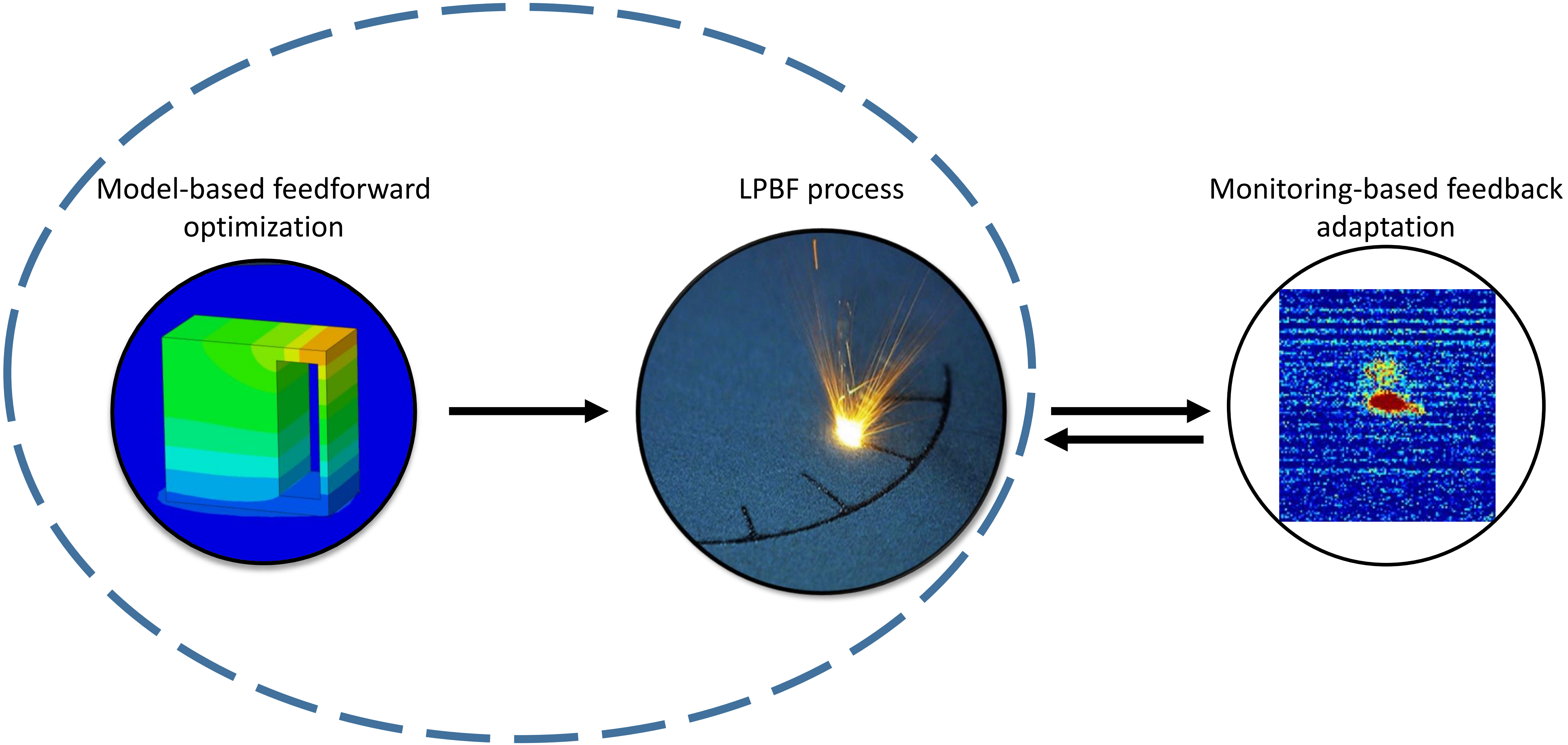
Part specific and **location specific** process parameters can be derived from numerical simulations and adaptive feedforward control.



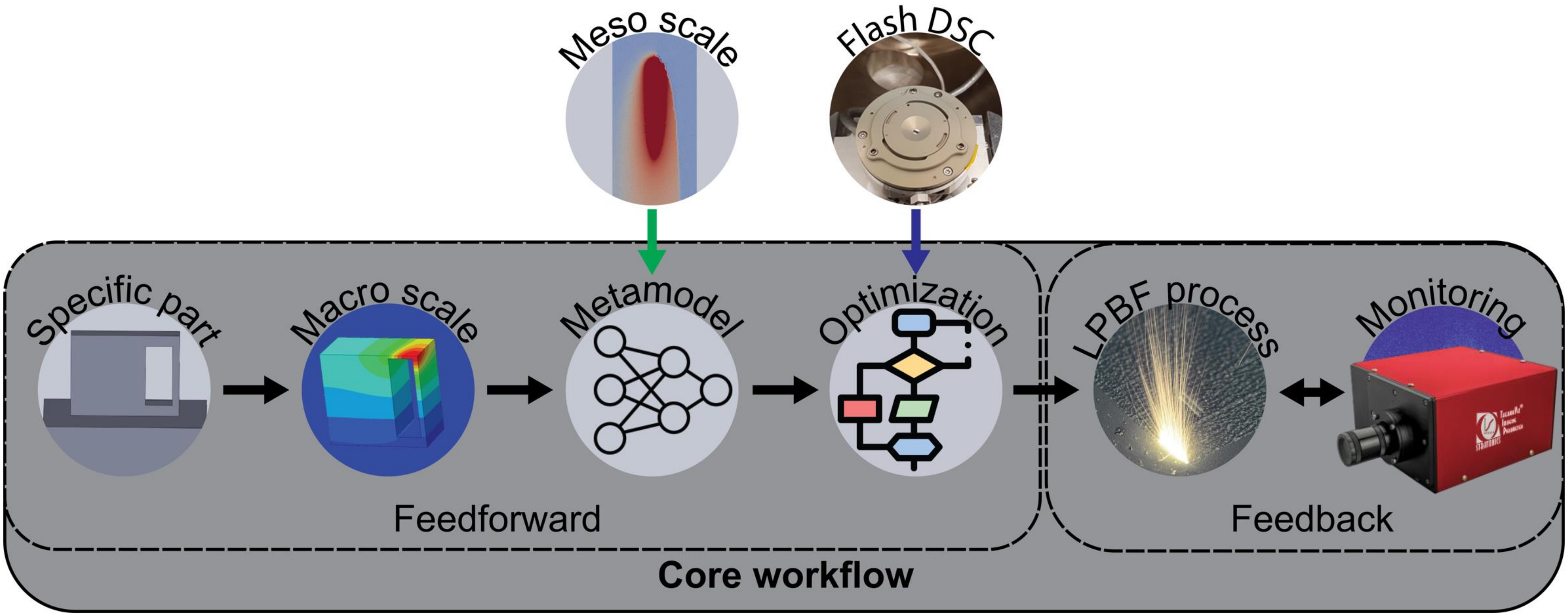
C.L. Druzgalski, et al. Additive Manufacturing, (2020)

Continuation of the PREAMPA (SFA) project

Overview – Proposed solution

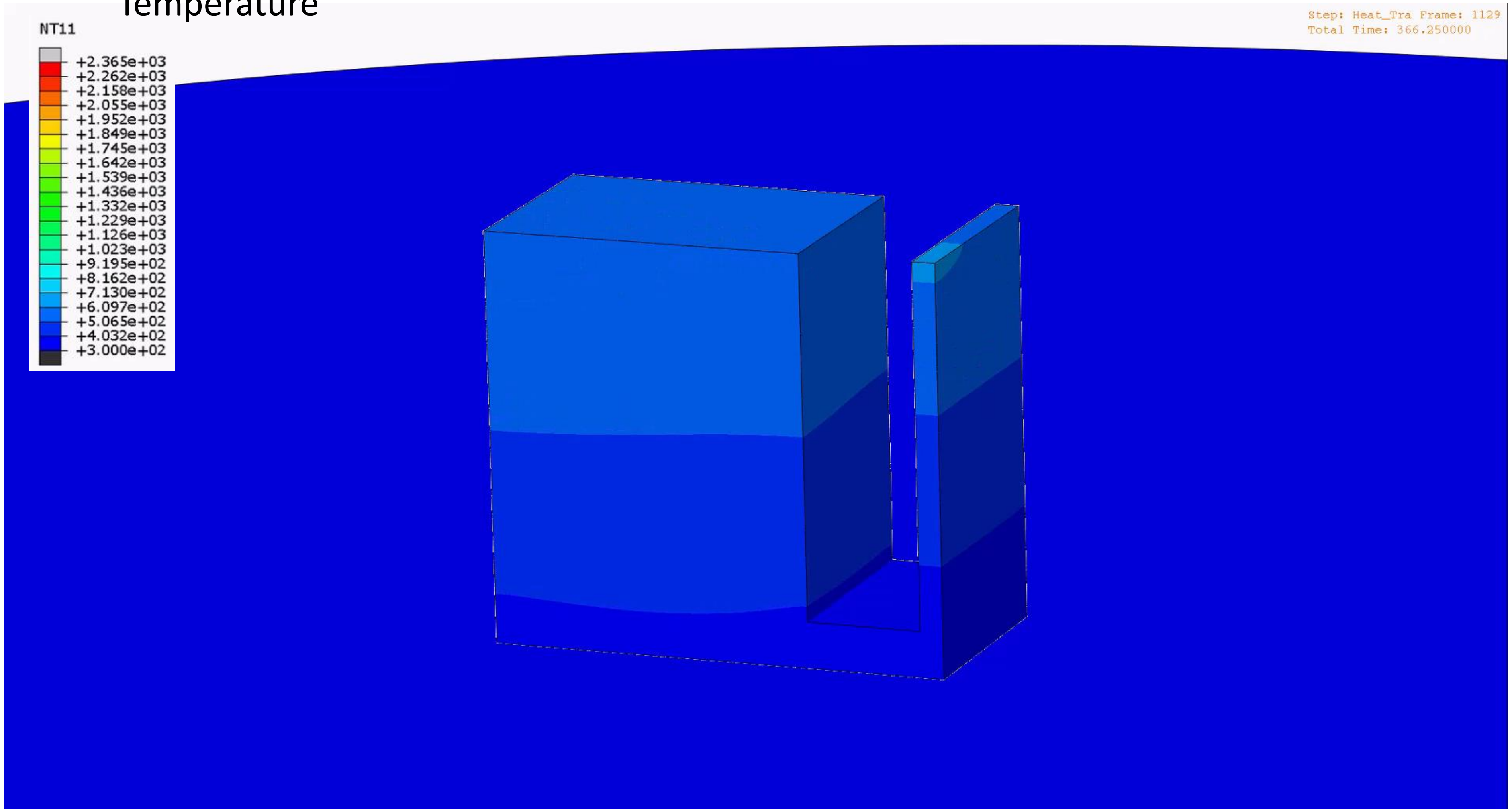


Project Work Flow

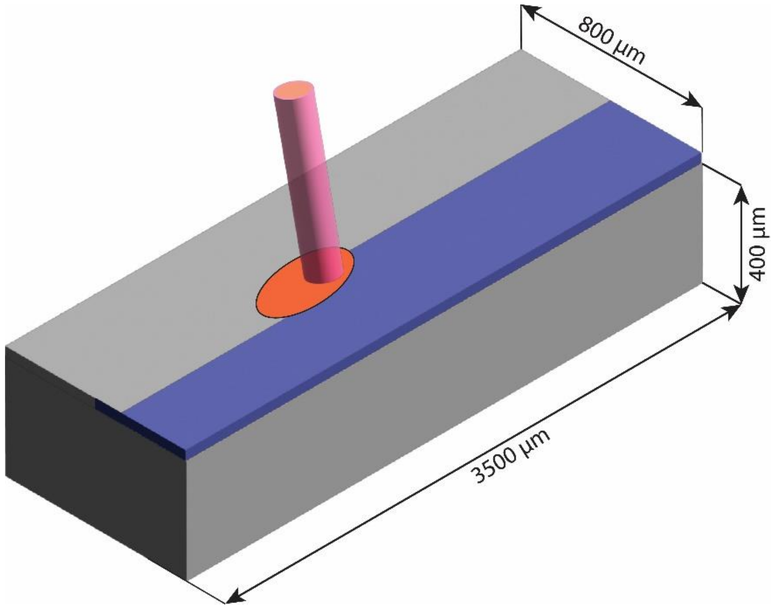


Macro-scale model

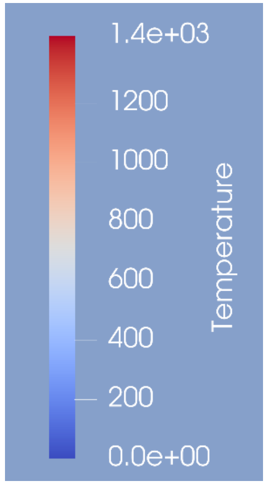
Temperature

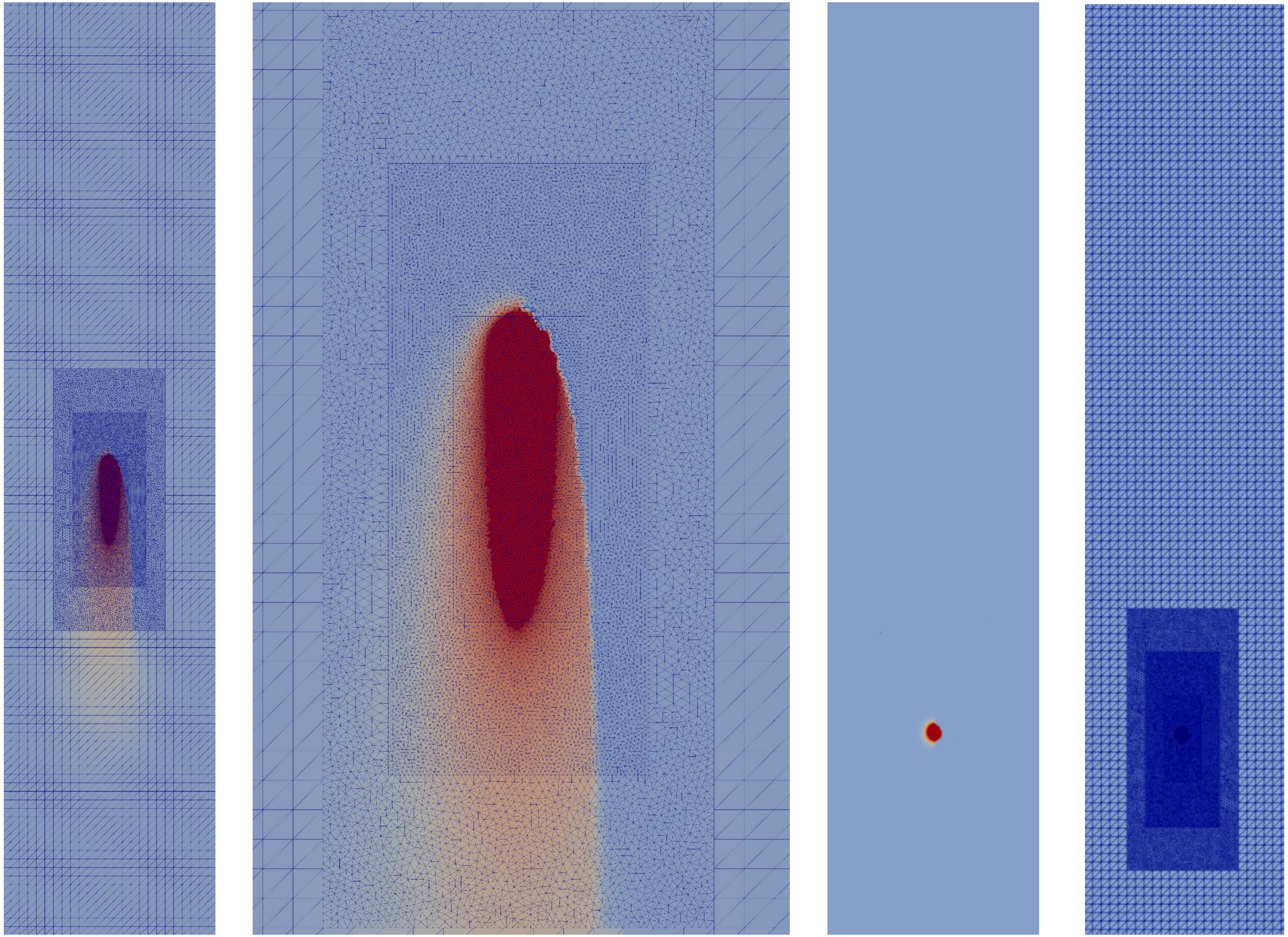


Mesoscale model



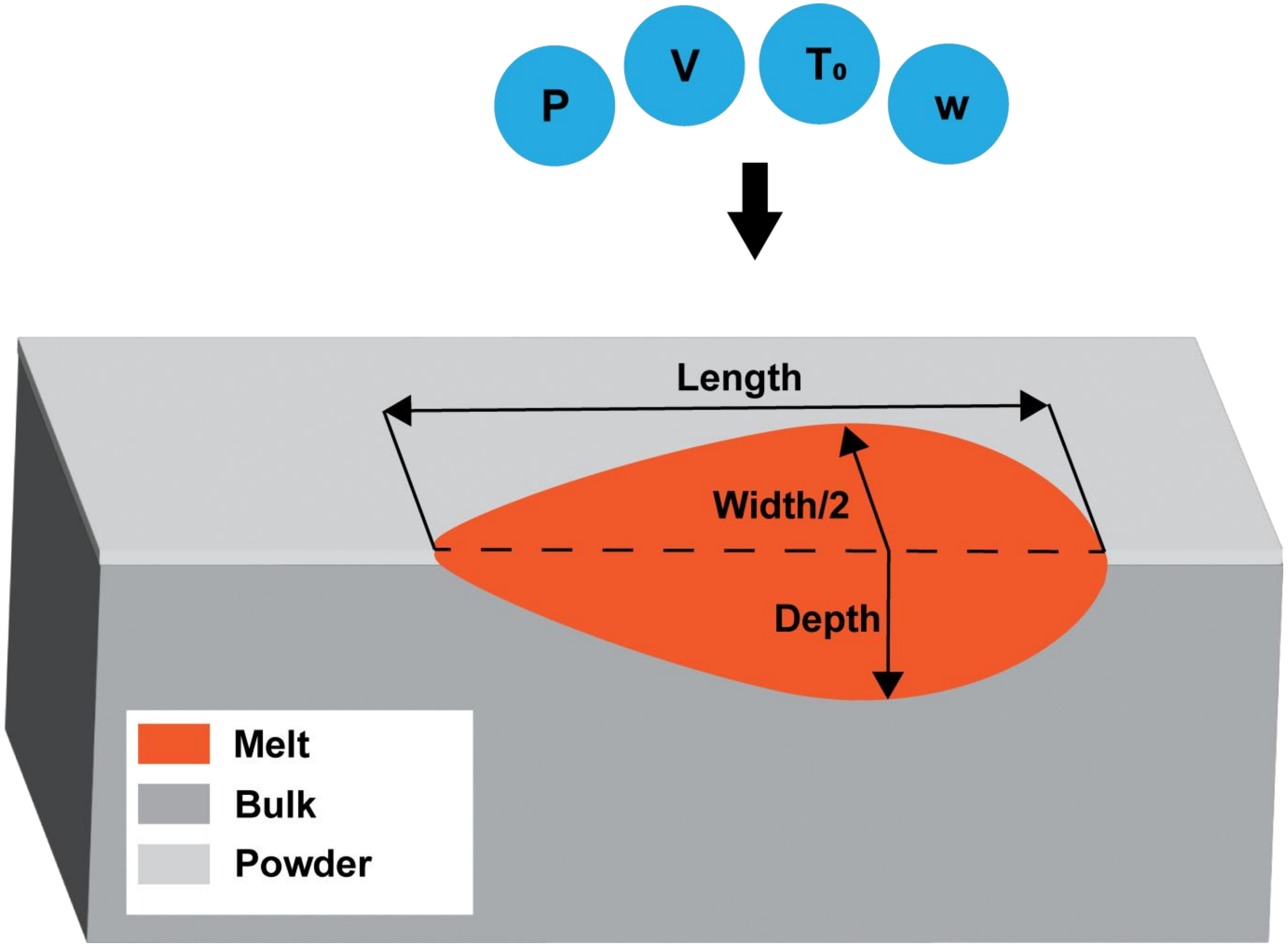
Temperature





- **Three media (solid, powder and liquid) with T dependent properties**
- **Path-dependent remeshing**

Objective: fully control the melt pool dimensions

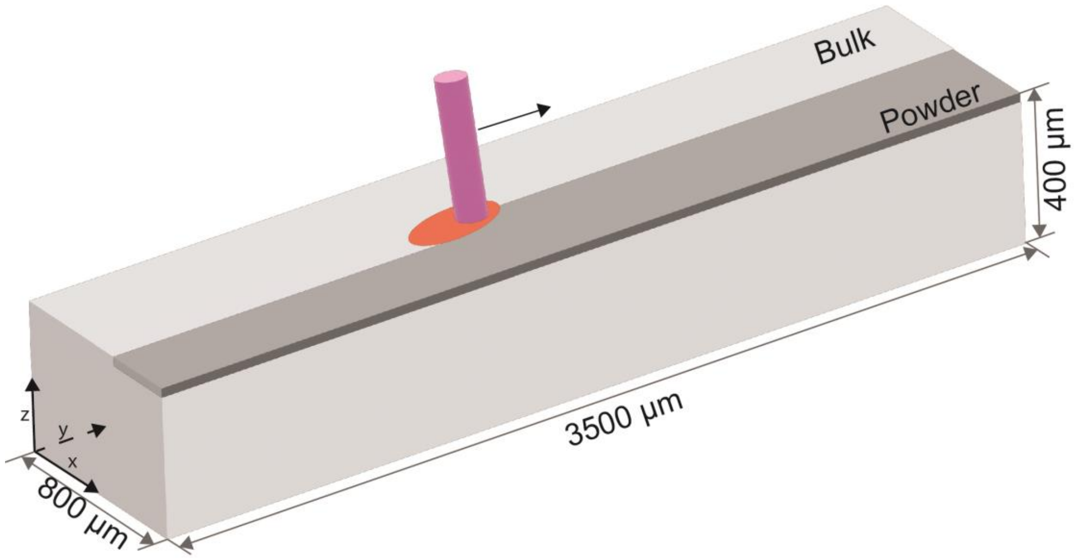


Important variables:

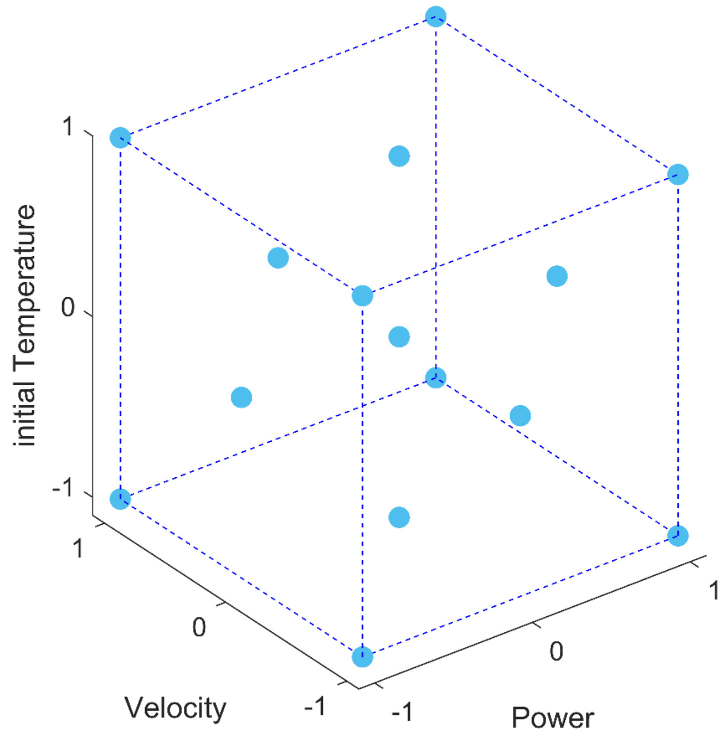
- P = laser power
- V = laser velocity
- T0 = initial temperature
- w = laser spot size

The **metamodel** : an approach to minimize the number of simulations

Numerical simulation



Design of Experiments
15 simulations (P, V, T0)



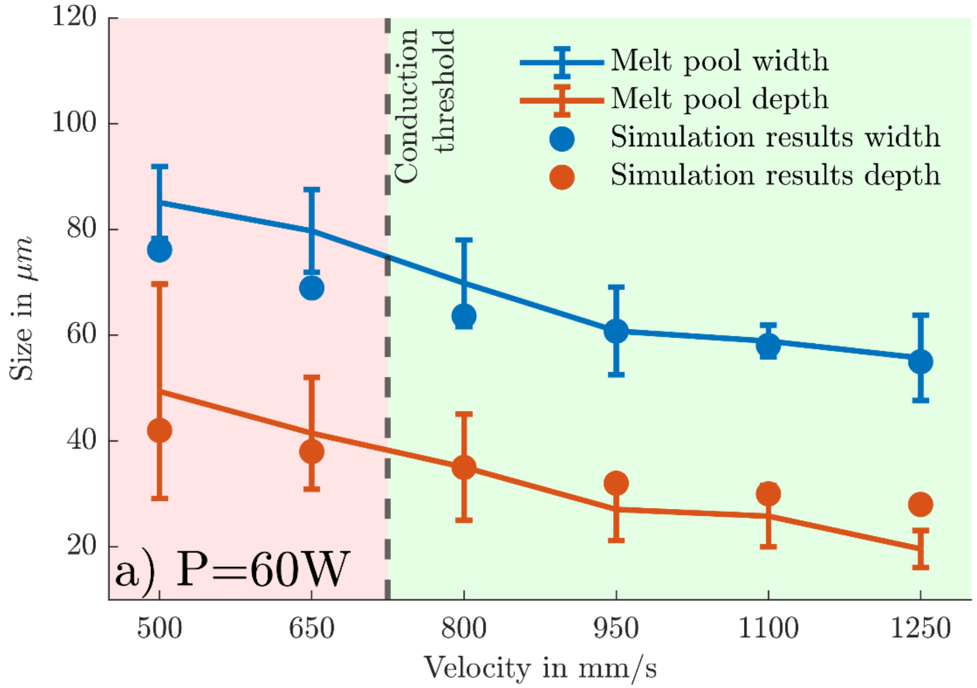
Recently : adding the laser beam spot size **w**

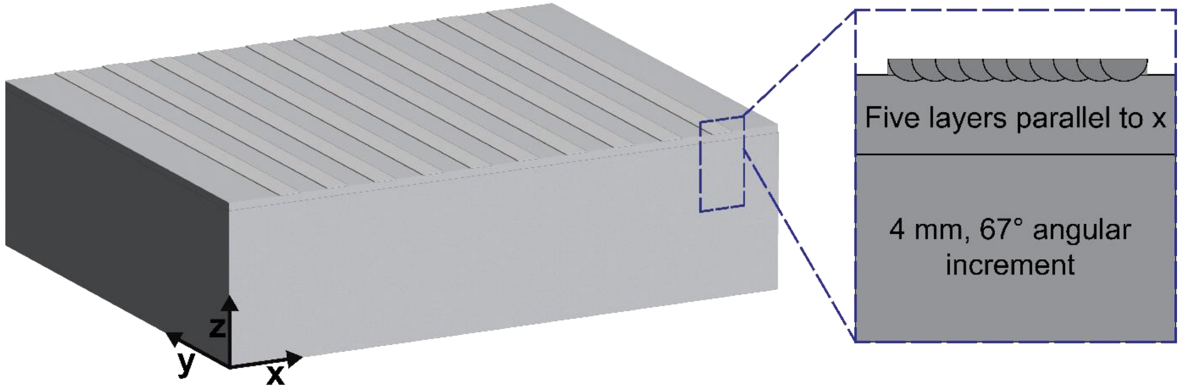
→ **translate** process parameters **from one machine to another**

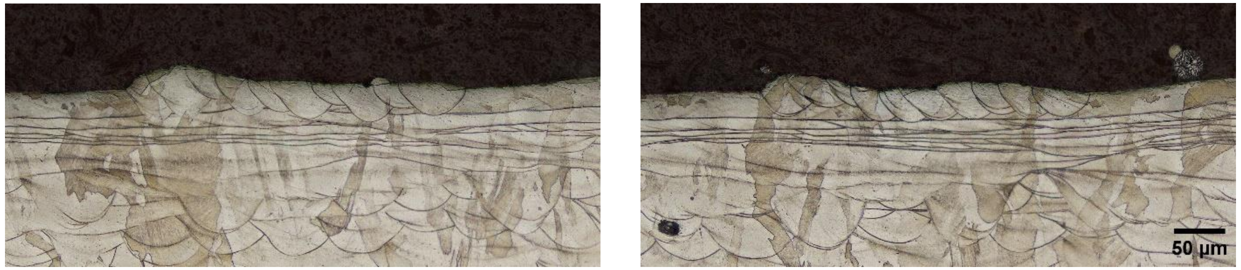
→ Only **25 simulations needed**

Experimental verification

- **316L stainless steel and Ti-6Al-4V**
- Spot size w of 30µm
- T0 = room temperature
- Min. 9 observations per process parameter combination







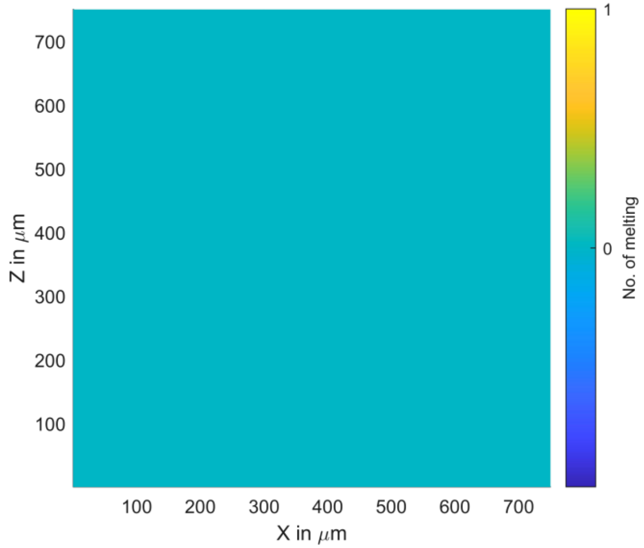
Lack of fusion processing maps

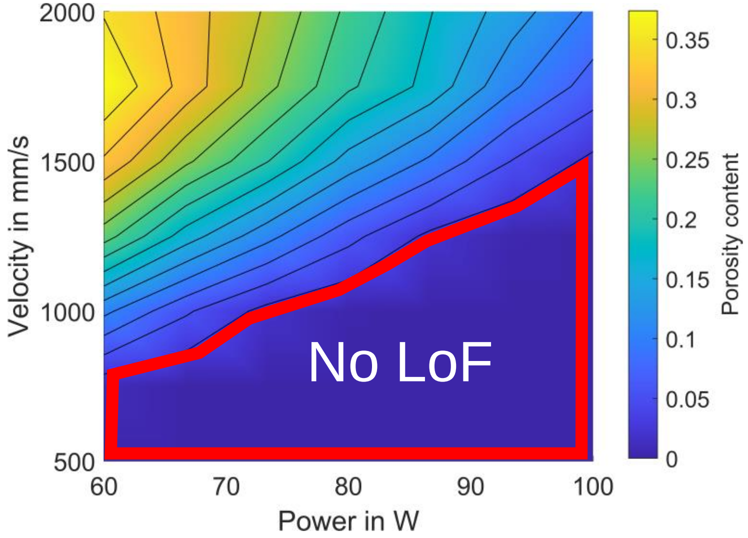
- Metamodel predictions

  → Fast **simulations** to efficiently estimate lack of fusion (LoF) defects, geometrically.

  → For given (P,V,T0,w) and defined scanning strategy

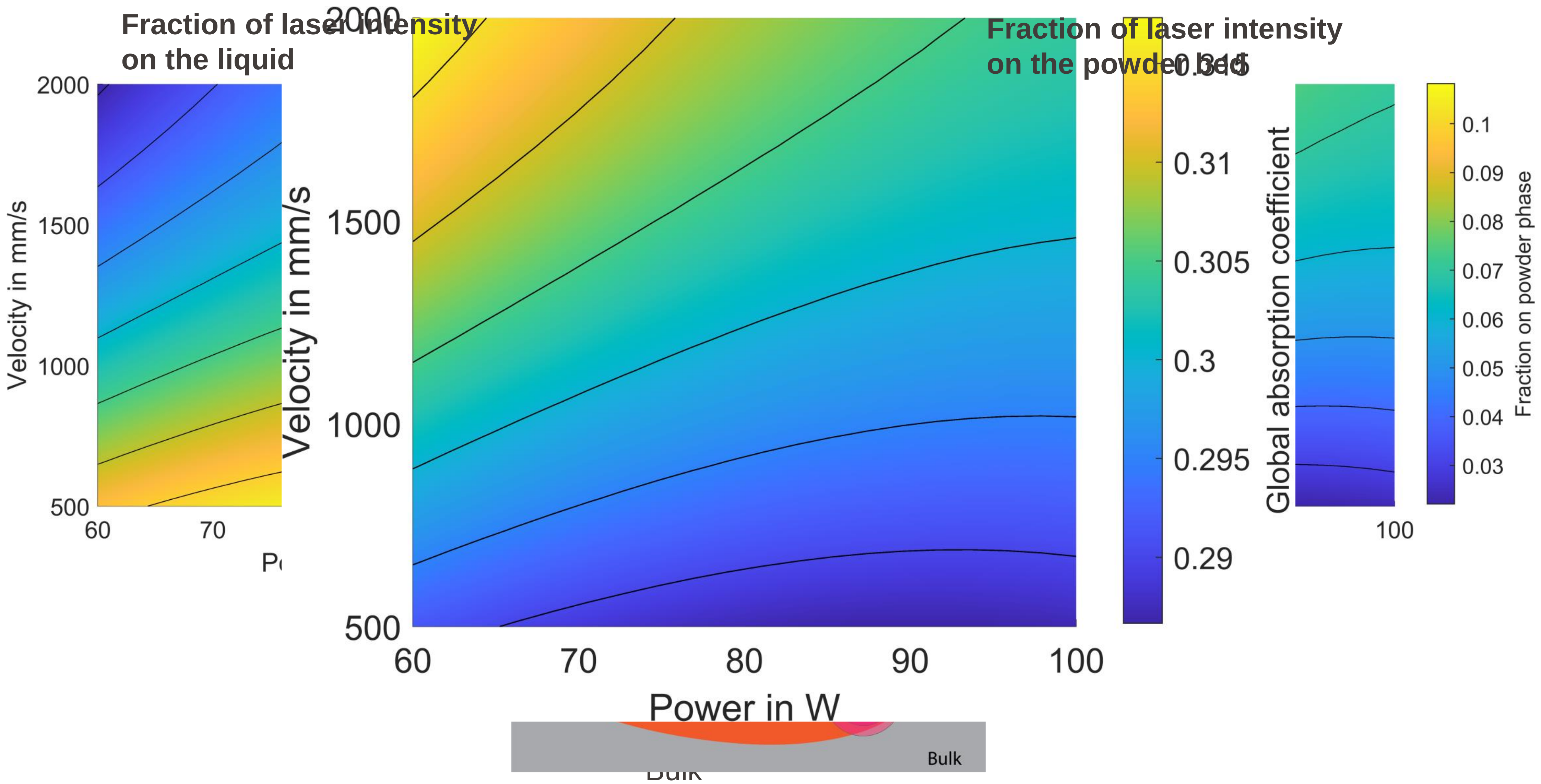
- **Process parameter maps** indicating lack of fusion (LoF) content, for a wide range of process parameters.



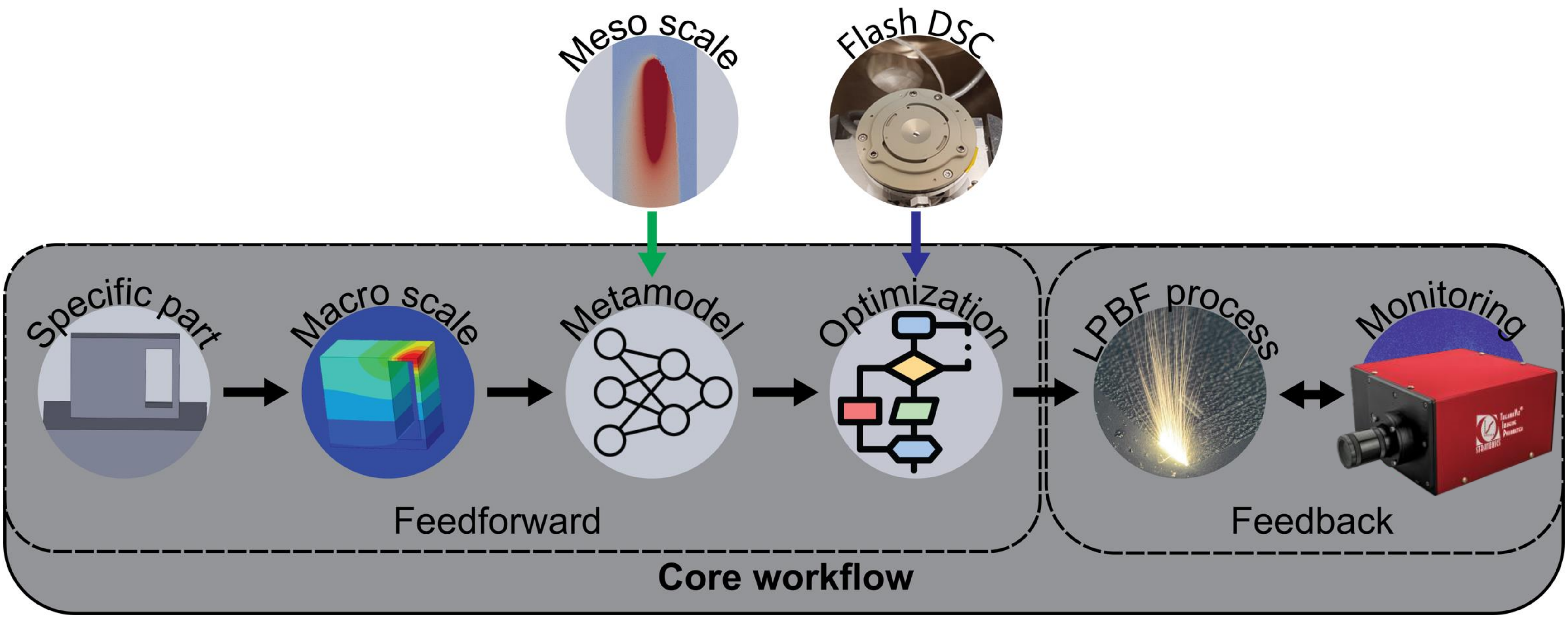


Establishing the global laser absorption coefficient

Lucas Schlenger



Project Work Flow

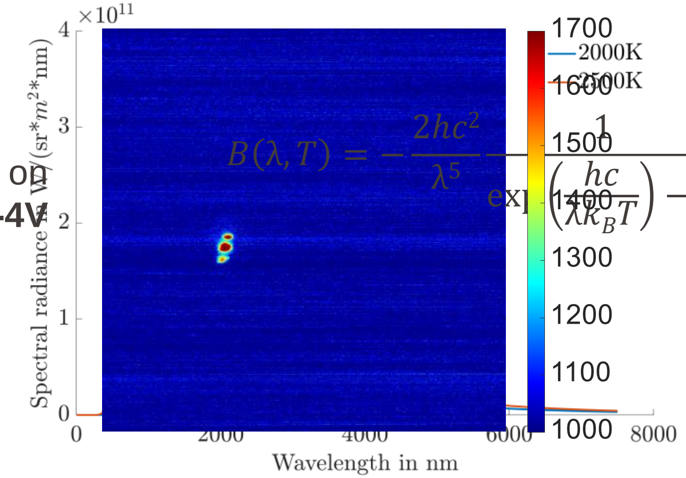


Process monitoring by dual wavelength thermal imaging

- Conventional (single wavelength) thermal imaging requires knowledge of the **spectral emissivity** of the surface.
- **Emissivity of a surface is a complex function** of surface chemistry, surface roughness, physical state and other parameters
  → very difficult to obtain reliable emissivity data, relevant for the LPBF process.
- **Remedy:** Measuring the intensity at **2 different wavelengths** allows to eliminate the emissivity from the equation.

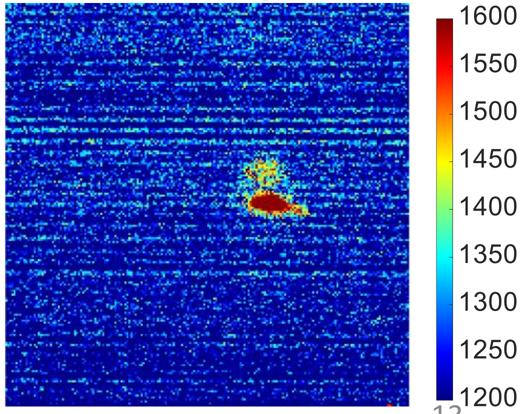
Spattering and melt pool oscilations during LPBF of **Tungsten**

Beam-shaping on **Ti-6Al-4V**



$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1}$$

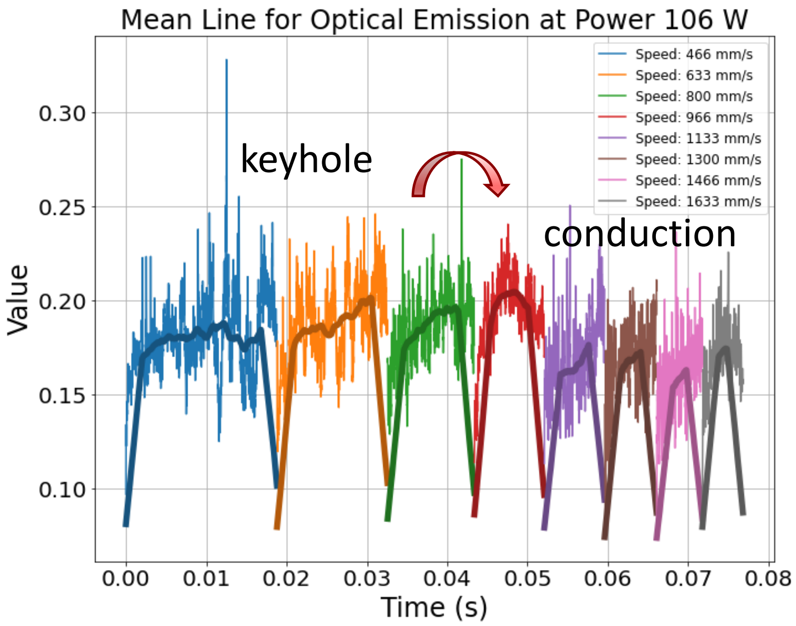
LPBF of **316L stainless steel**

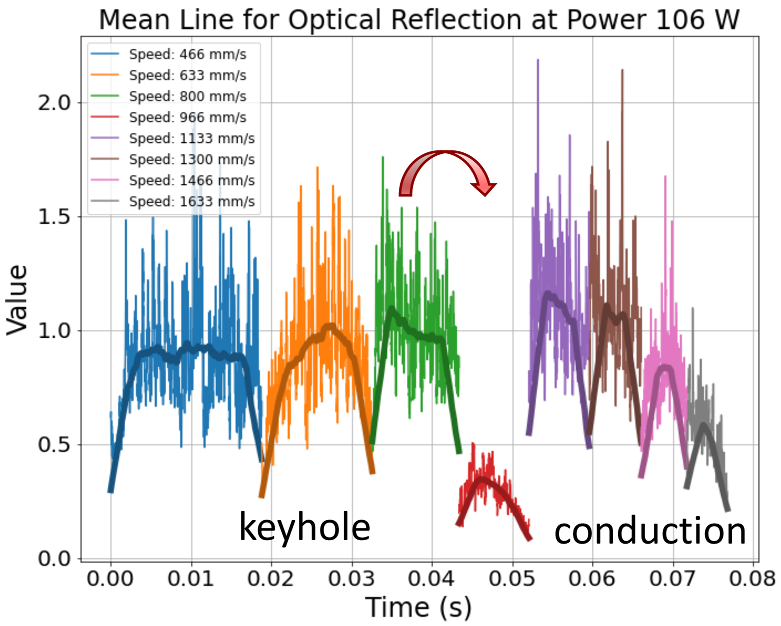


Optical Data Analysis Across LPBF Parameters

Evaluating Optical Emission and Reflection Variability

- **Dual-Channel Analysis:** Optical Emission and Reflection for LPBF process insights.
- **Sensors:** Si Photodiodes and InGaAs sensors.
- **Speed & Optical Correlation:** Analysis of how laser speed affects optical responses, key for process control.
- **Observation:** A clear peak in optical emission and a trough in reflection are indicative of the transition from keyhole to conduction mode.





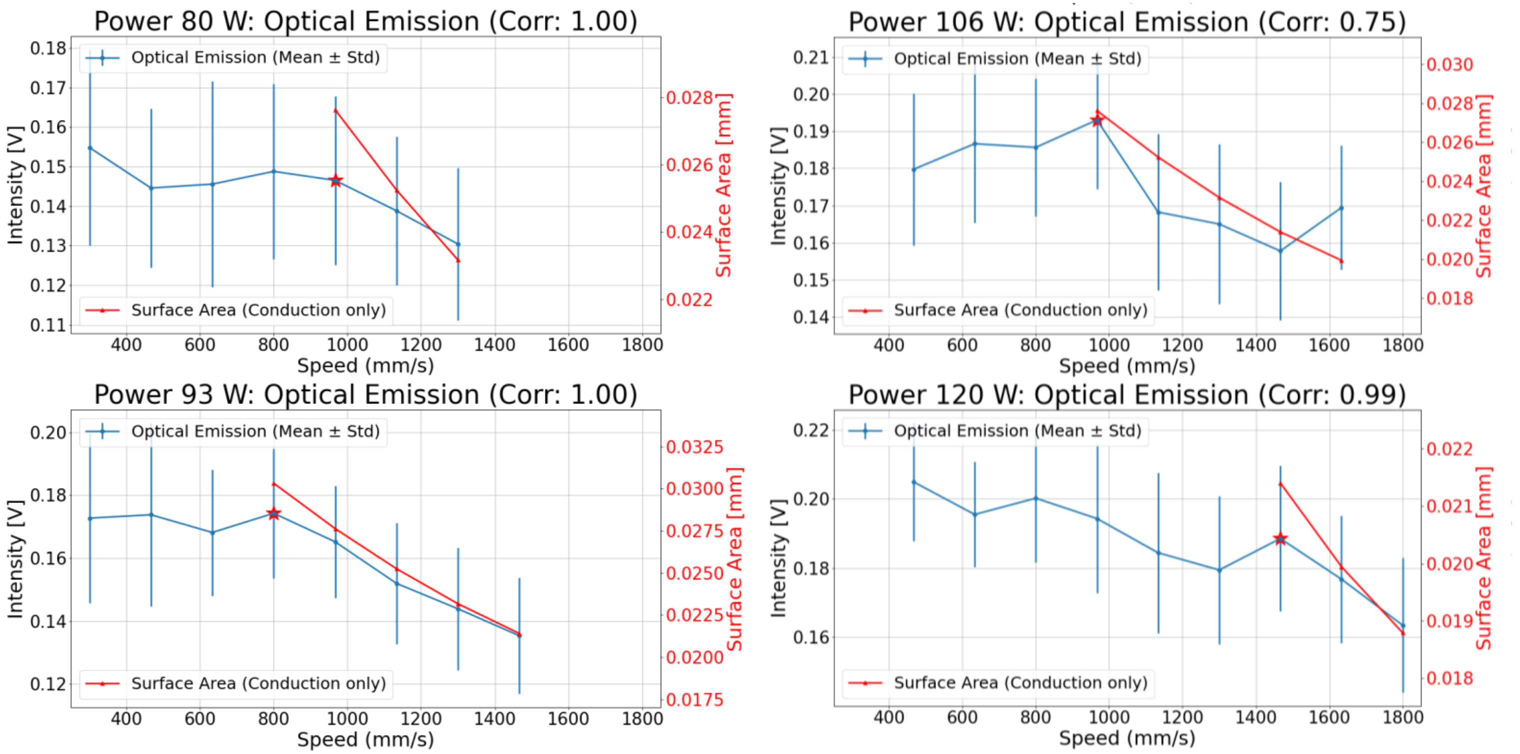
Evident **peak** in **optical emission** and **bottom** in **optical reflection** signaling regime transition: from **keyhole** to **conduction**

Real-Time Control of Melt Pool Geometry

Harnessing Optical Signals for Precision in LPBF

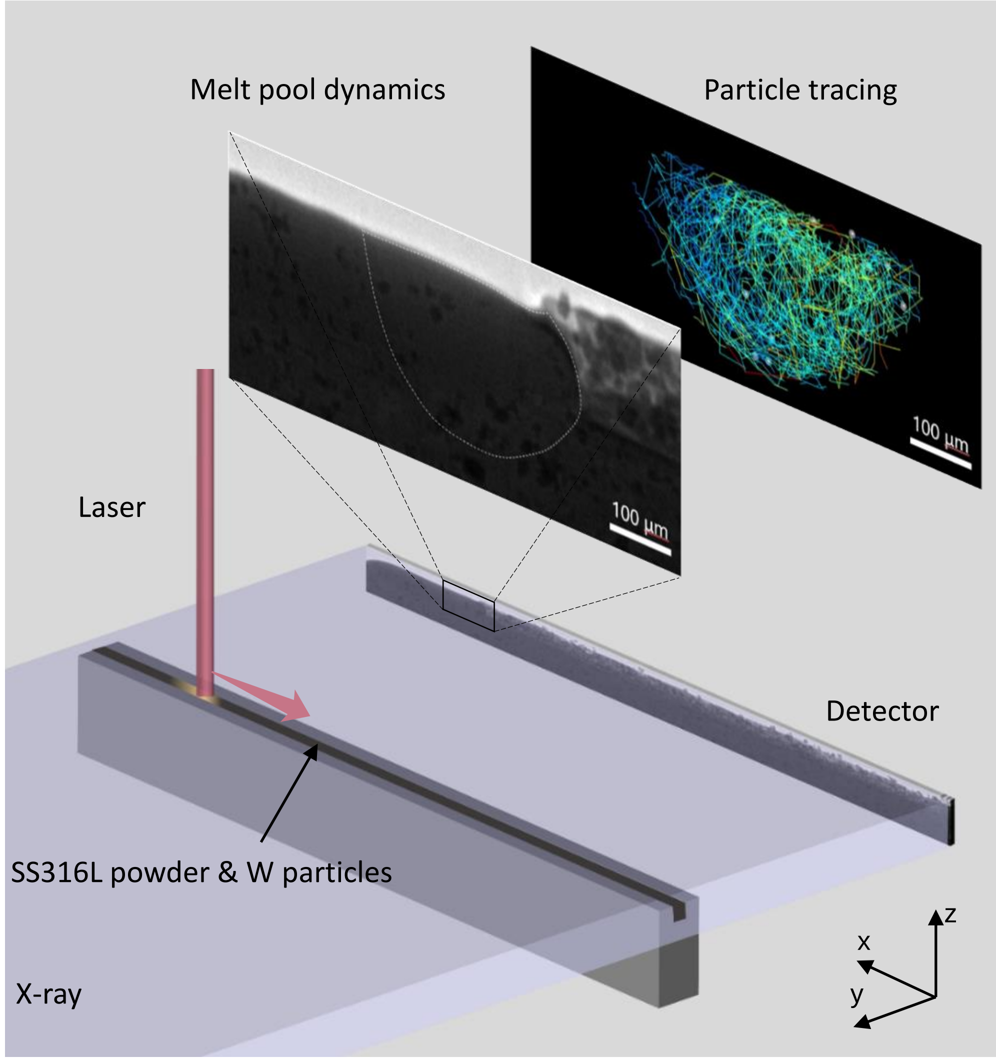
- **Optical emission:** Significant correlation with Surface Area, pivotal for melt pool geometry control.
- **Correlation for Quality:** With a correlation close to 1, real-time monitoring of optical emission becomes a reliable indicator for maintaining the precise size of the melt pool, ensuring the integrity of printed details.
- **Process Optimization:** This high correlation allows for predictive adjustments during printing, enhancing the quality and detail of LPBF-manufactured components.

  → planned in 2024

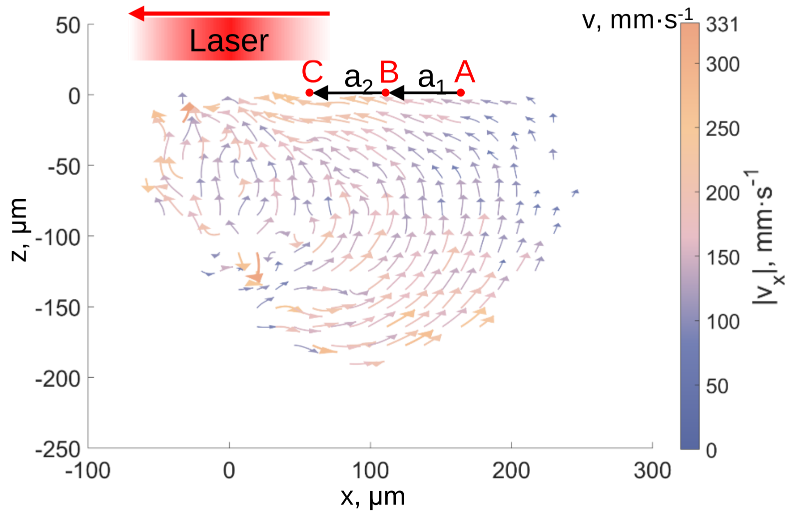


Experimental Quantification of melt pool dynamics

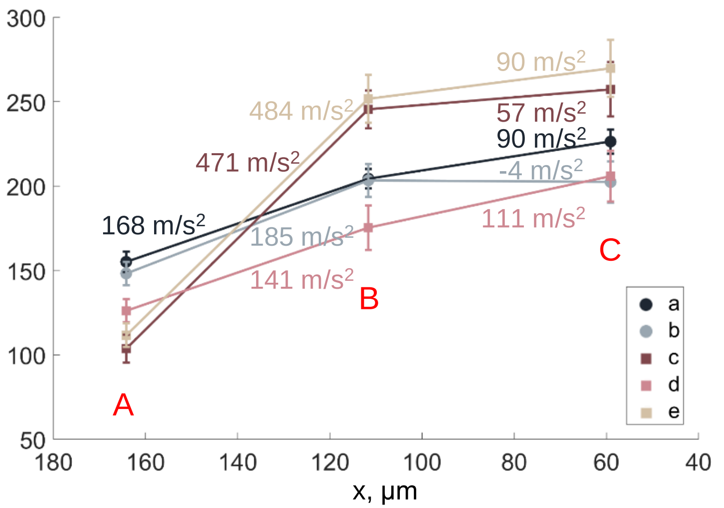
In-situ synchrotron X-Ray imaging of SS316L LPBF with W tracers at TOMCAT, PSI



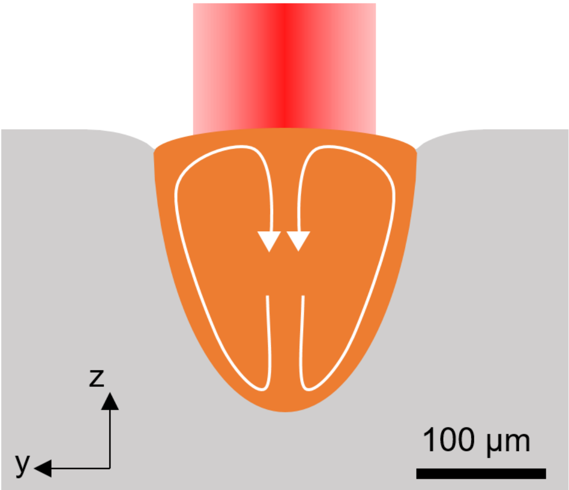
Experimental setup



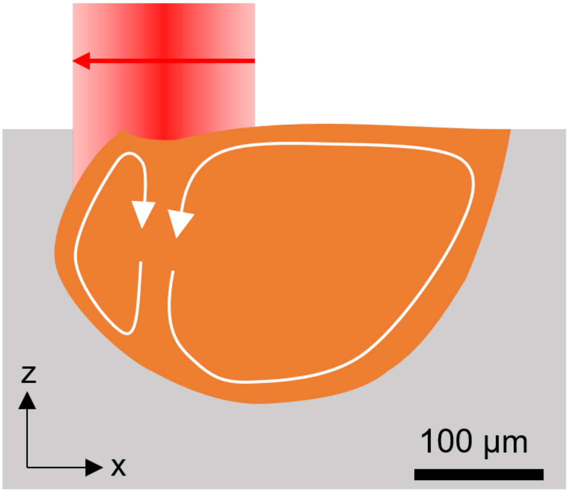
Measured fluid velocity field



Marangoni effect from A to C



Front view of flow pattern



Side view of flow pattern

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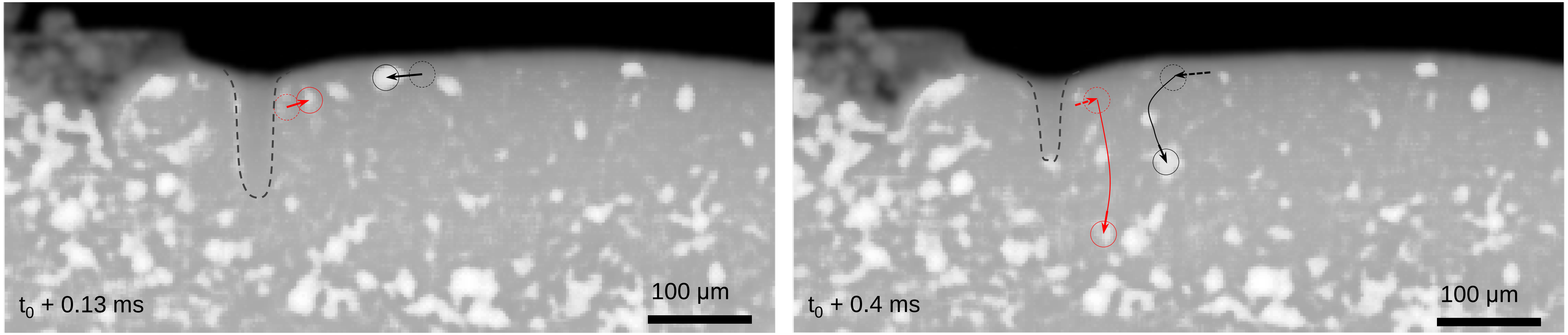


Coexistence of outward (red) and inward (black) flows in keyhole mode

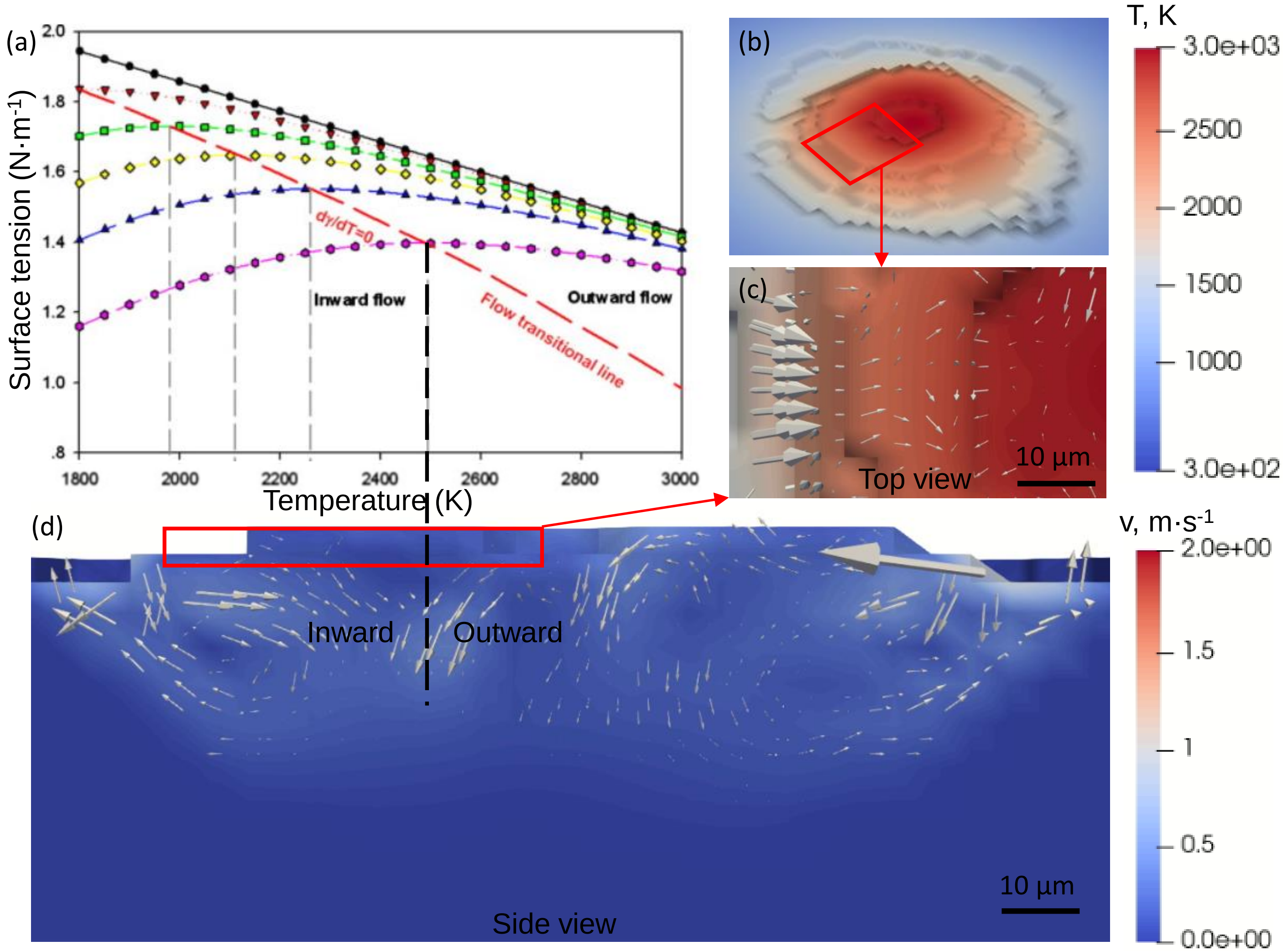
Key findings:

- The presence of inward Marangoni flow due to surfactant contaminations in commercial stainless steel powder
- Shift of conduction-keyhole threshold towards higher energy input as a result of inward Marangoni convection
- High-resolution quantification of melt pool dynamics as valuable references for CFD modeling
- Insights for further research to explore the pore-free process window by controlling the melt flow directions

CFD modeling of LPBF with OpenFOAM (in progress)

Empa
Materials Science and Technology

The importance of calibrating temperature-dependent surface tension coefficient



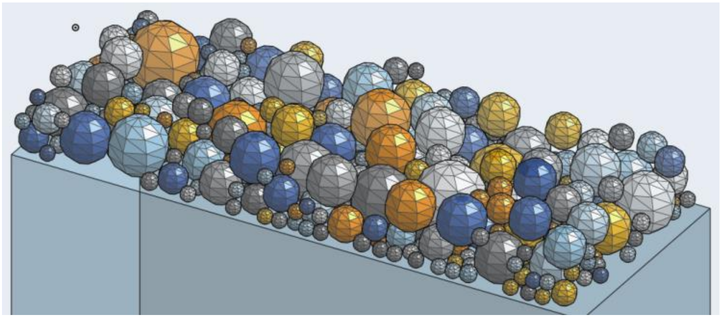
(a) Surface tension – Temperature relationship (C.X. Zhao et al., *Acta Materialia,* 2010); (b-d) Simulated melt pool temperature and flow flied.

Key influences:

- More realistic melt flows
- Changes in melt pool temperature and dimensions (deeper as more inward flows)
- Potential impacts on keyhole's formation

Next steps:

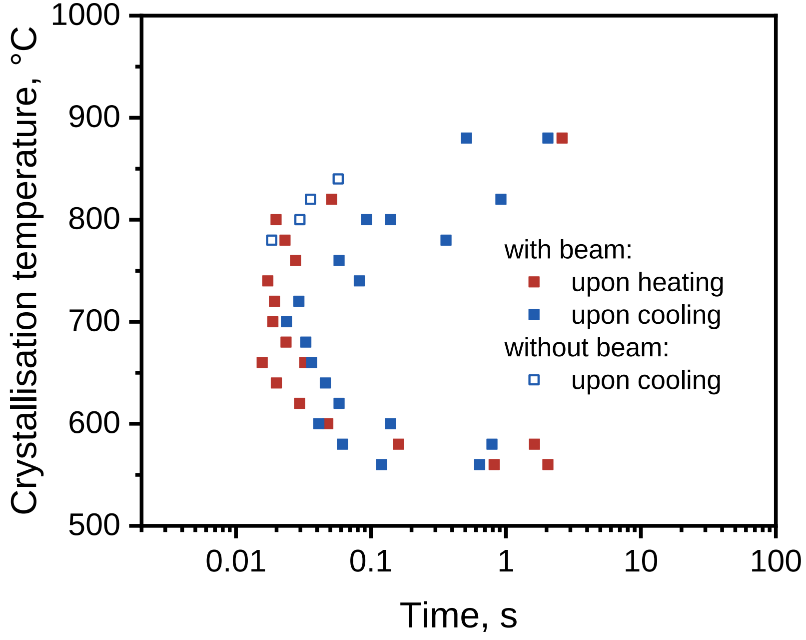
- Multiple reflections module
- Impact of realistic powder distribution



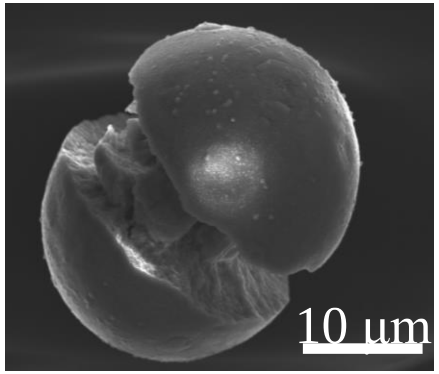
TTT-diagrams of Bulk Metallic Glasses

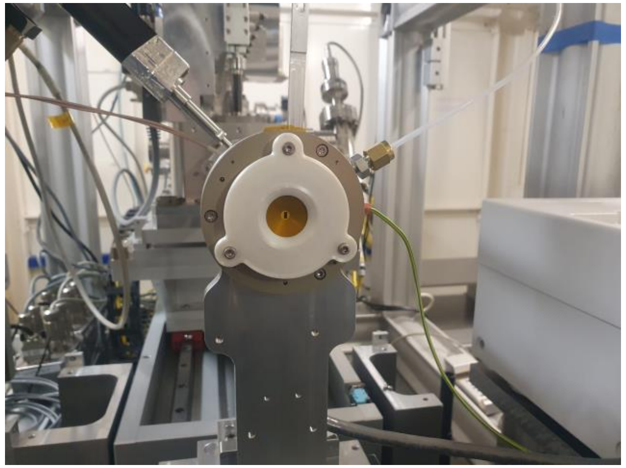
- TTT diagrams measured to investigate crystallization kinetics of BMGs in conditions close to those simulated in LPBF
- Variations were found within powder samples and from one powder to another
  - → BMG behavior very sensitive to thermal history
  - → Used for assessing accuracy of thermal modelling

TTT diagram



- TTT diagram measured *in situ* in a synchrotron X-ray beam with an optimized set-up
  - Better reproducibility achieved but sample degradation cannot be completely avoided →
  - Design and construction of a steel vacuum chamber
  - Allows FDSC measurements in vacuum or inert atmosphere





Conclusions

- Macroscale and mesoscale models have been developed for the prediction of thermal fields and melt pool size and geometry in LPBF conditions
  - Mesoscale model transformed into a fast metamodel (P,V,T0,w), fully calibrated for two materials
  - Sensitivity to the laser beam size w means possible translation to other LPBF machines
  - Prediction of Lack of Fusion maps
- The simulations can be used for a first version of the feedforward control of the process
- Adaptation can be achieved with optical measurements using optical sensors, indicating
  - Transition from conduction mode to keyhole
  - Changes in melt pool surface area
- More advanced feedback is now possible using dual wavelength thermal imaging

Monitoring-based adaptation (2024)

- Quantification of melt pool dynamics and first developments in CFD modelling will help improving the simulations and the prediction of transition to the keyhole regime
- Accuracy in thermal modelling assessed based on the new TTT diagrams obtained for Bulk Metallic Glasses (BMGs), and those to come with the new design of the FDSC device

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