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HPC4MDF

Providing US Manufacturers with a Simulation Framework for Directed Energy Deposition (DED) Additive Manufacturing

PRESENTED BY

Stephen DeWitt

Senior Computational Scientist
Computational Sciences and Engineering Division

U.S. DEPARTMENT of ENERGY

ORNL IS MANAGED BY UT-BATTELLE LLC
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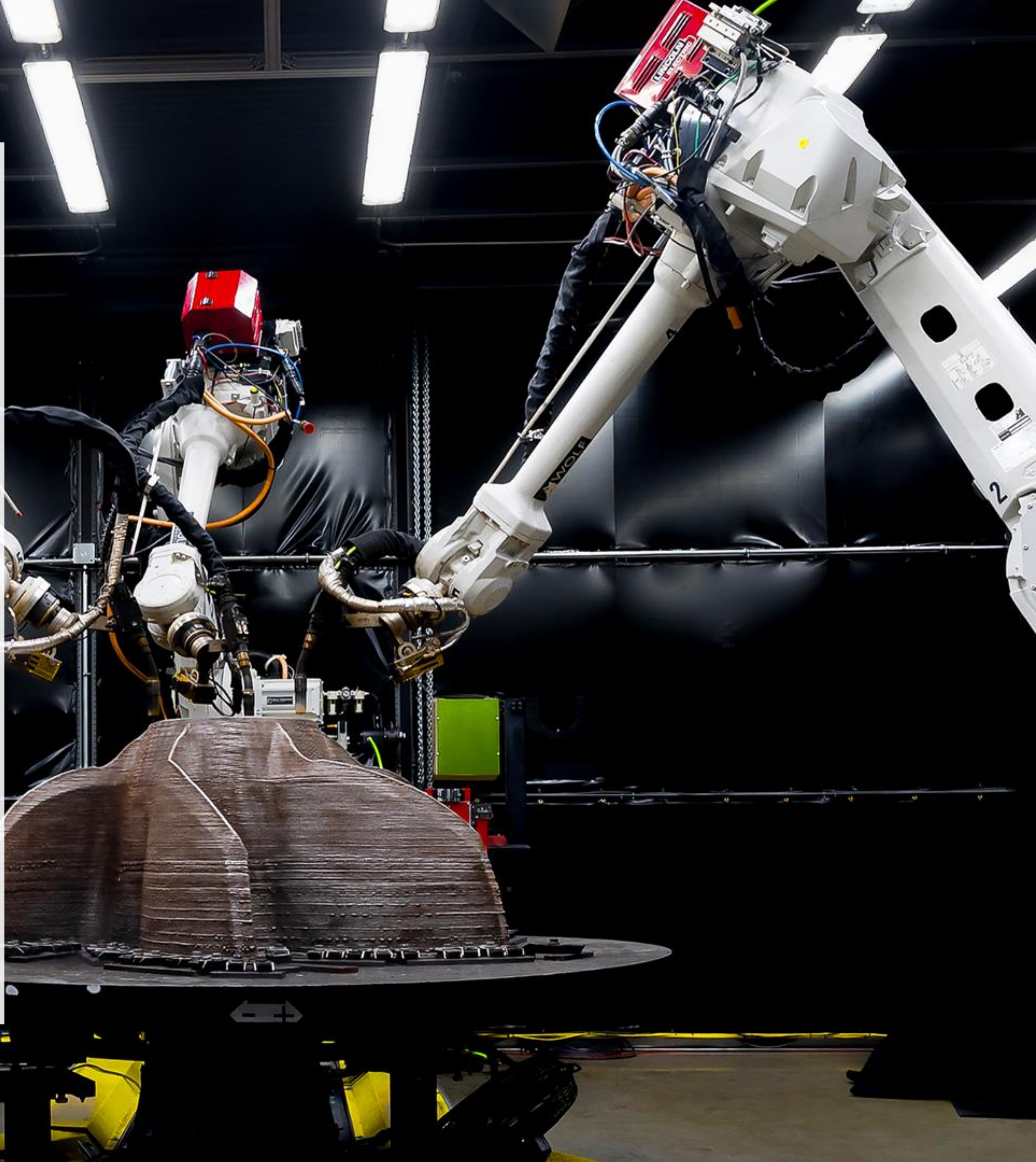
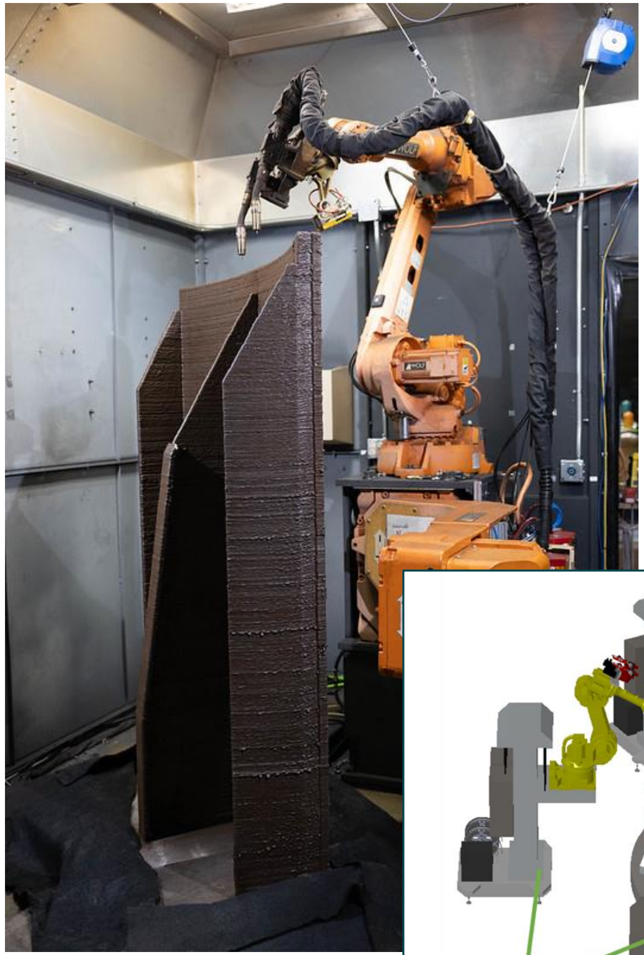


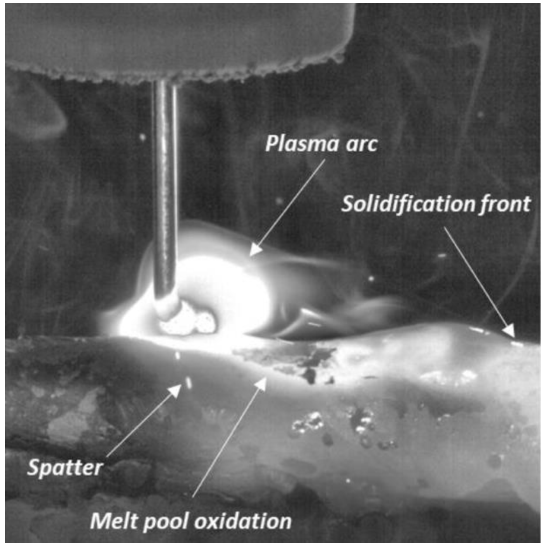
US manufacturers need resilient supply chains for large-scale metal components

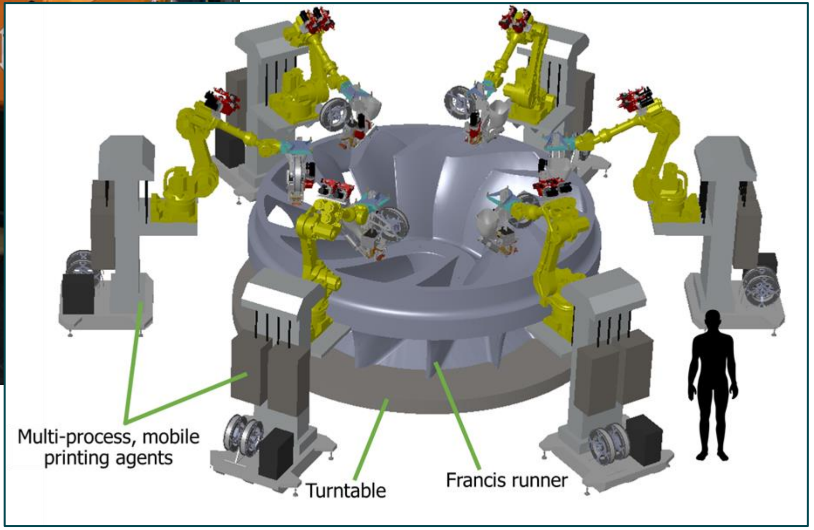
Lead times are too long for large castings (years)

Most large-scale foundries are outside the US

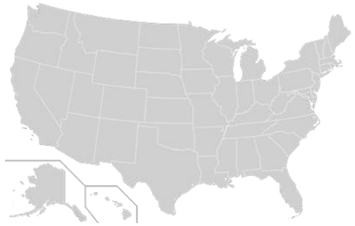
Wire-arc additive manufacturing (WAAM) is a promising alternative to casting for large-scale metal components







- **Shorter lead times**
- **Agile production**



- **Domestic suppliers**
- **Path to qualification via welding standards**

US manufacturers need an improved simulation toolchain for large-scale WAAM to predict location-specific properties

Bigger parts mean longer prints and more costly iteration on process parameters

Existing **commercial simulation tools lack the computational performance** needed for these workflows

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AMMTO funded HPC4MDF to tackle this challenge, integrating unique capabilities at LLNL and ORNL into the Manufacturing Demonstration Facility ecosystem

ORNL MDF Team
Matt Rolchigo, John Coleman, Ashley Gannon, Bruno Turcksin, Daniel Arndt, Gerry Knapp, Bhagya Prabhune, Yousub Lee, Shramana Ghosh, Alex Plotkowski

LLNL Team
Tim Dunn, Jerome Solberg, Saad Khairallah

Funding
This project is funded by the US Department of Energy, Office of Critical Minerals and Energy Innovation, Advanced Materials and Manufacturing Technologies Office.

Facilities
This project used resources from the Manufacturing Demonstration Facility at ORNL, the Oak Ridge Leadership Computing Facility at ORNL, the CADES computing environment at ORNL, and the Livermore Computing Complex at LLNL.

In HPC4MDF we are developing a smart framework for large-scale DED and demonstrating its use

Develop a DED smart manufacturing framework

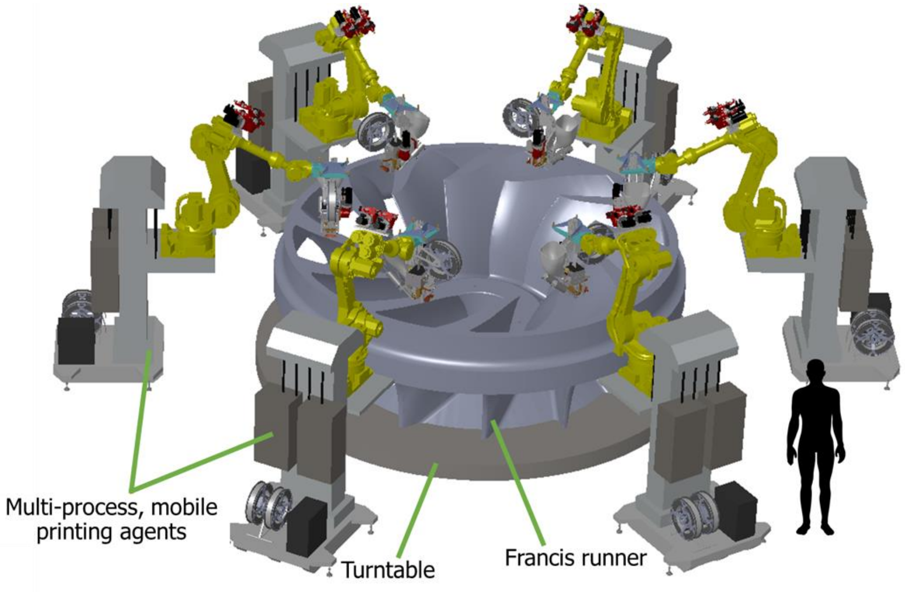
- *Spatial variability of thermal conditions and microstructure*
- *Cloud-deployable*

Demonstrate the framework for a DOE-relevant problem

- *AMMTO/WPTO Rapid RUNNERS hydrorunner*

Framework can both be used directly and to derisk commercial code development

Rapid RUNNERS is a FY26-28 DOE project to demonstrate the viability of additive manufacturing for hydroelectric turbine runners



System concept render

Target Wilson runner

4.3 m diameter

32 tons

VOITH
OPEN MIND THE CAM FORCE
TVA
Newport News Shipbuilding A Division of HII
EPRI
ARC SPECIALTIES AUTOMATED MANUFACTURING SYSTEMS

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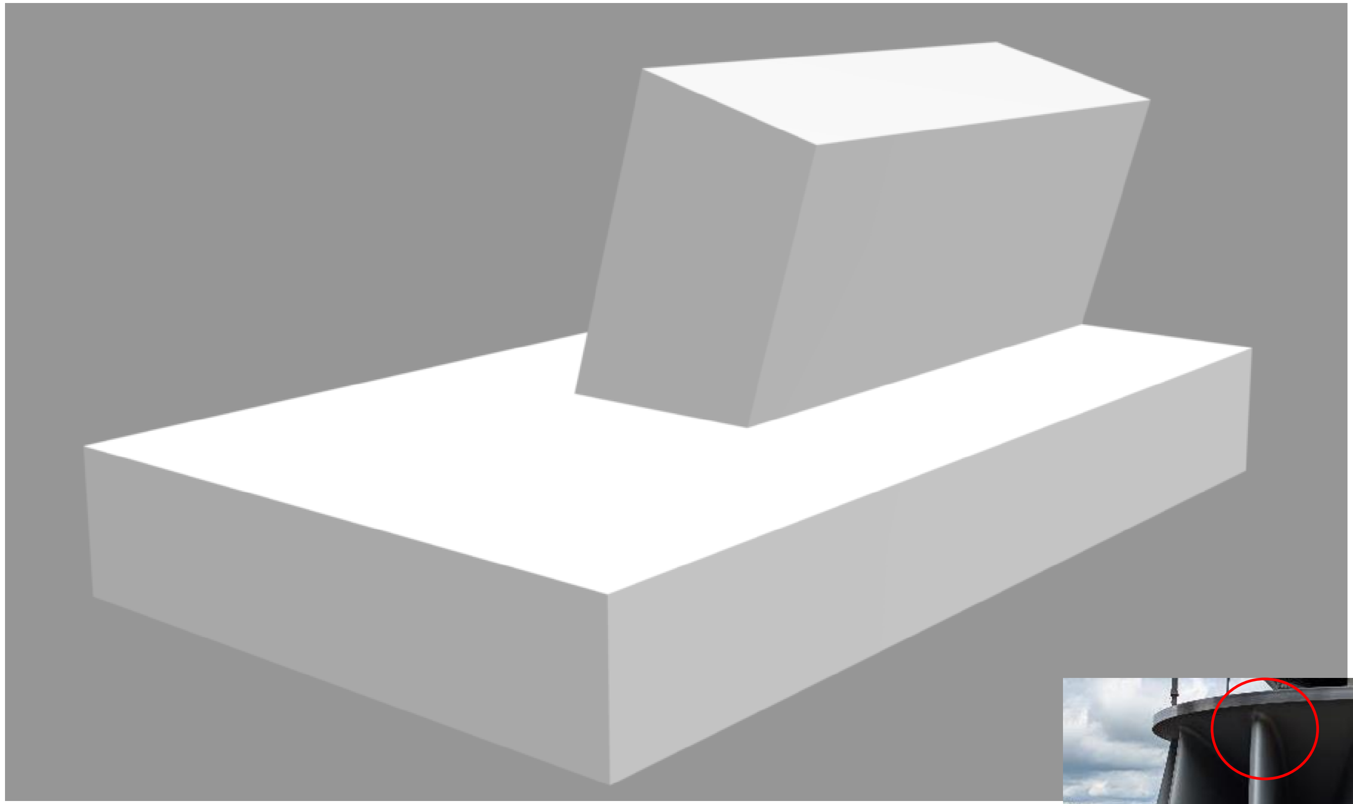
One of the FY26 deliverables for Rapid RUNNERS is a WAAM print of a representative T-joint between the blade and band



This is our initial demonstration component for the HPC4MDF framework

Rapid RUNNERS has several simulation-relevant challenges

The prints are huge

Large meshes, long simulated times, high stakes

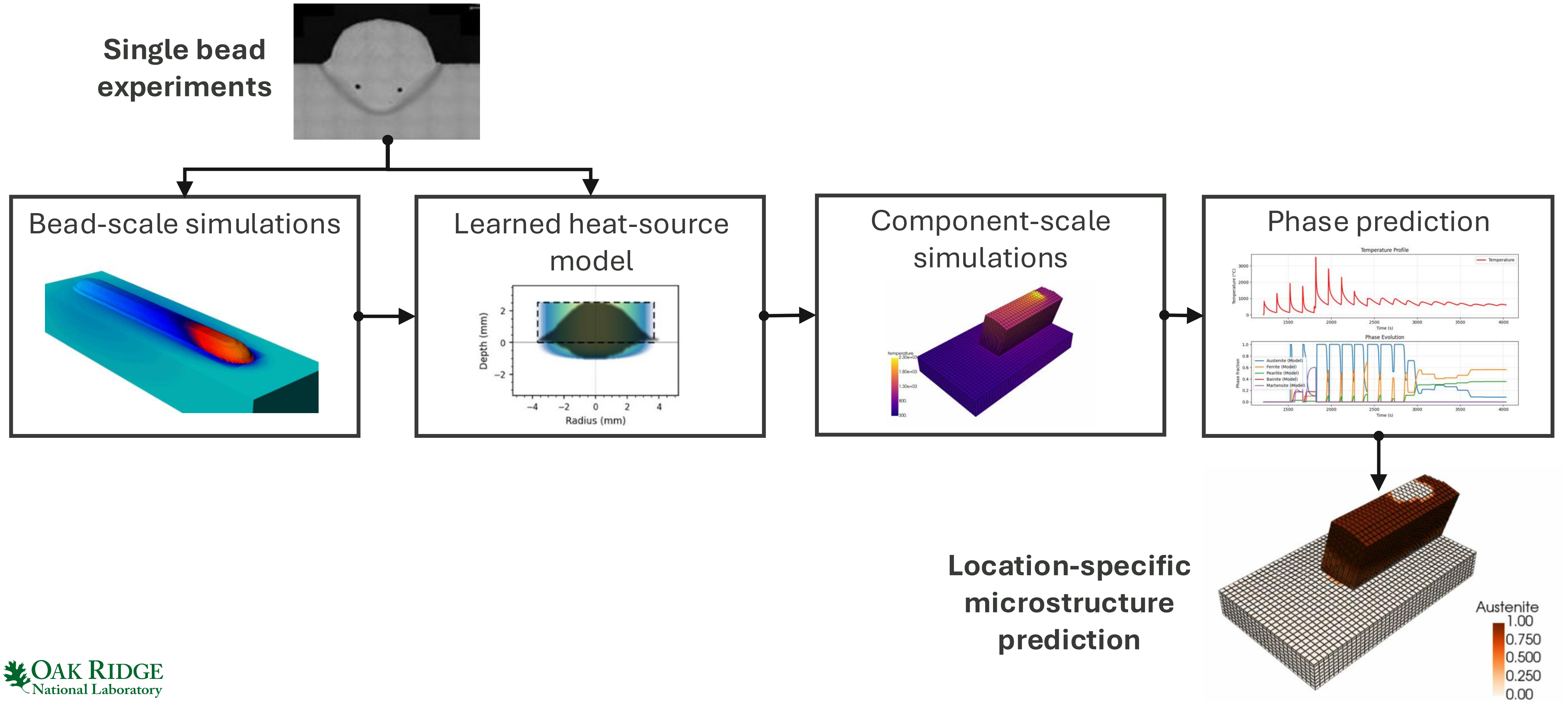
Multiple robots are printing the part

Simulations must support multiple heat sources and 5-axis toolpaths

Solid-state phase transitions matter for 410 stainless steel

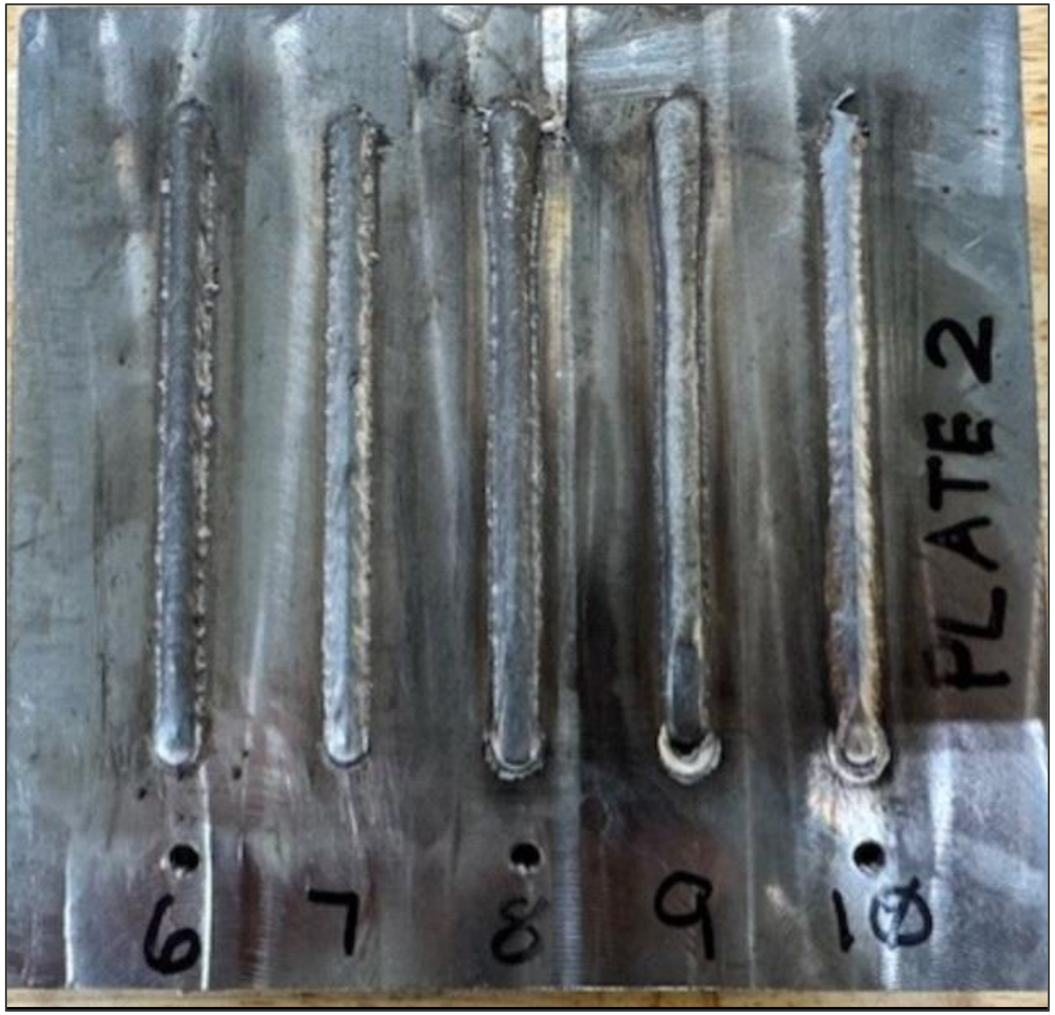
Retained δ-ferrite, hydrogen embrittlement in martensite, transformation strains

The HPC4MDF framework turns single-bead experiments into microstructure predictions across a part



Let's take a look at how the HPC4MDF smart manufacturing framework makes this prediction

First, we performed 10 quick single-bead experiments at the MDF for a variety of travel speeds and wire feed rates



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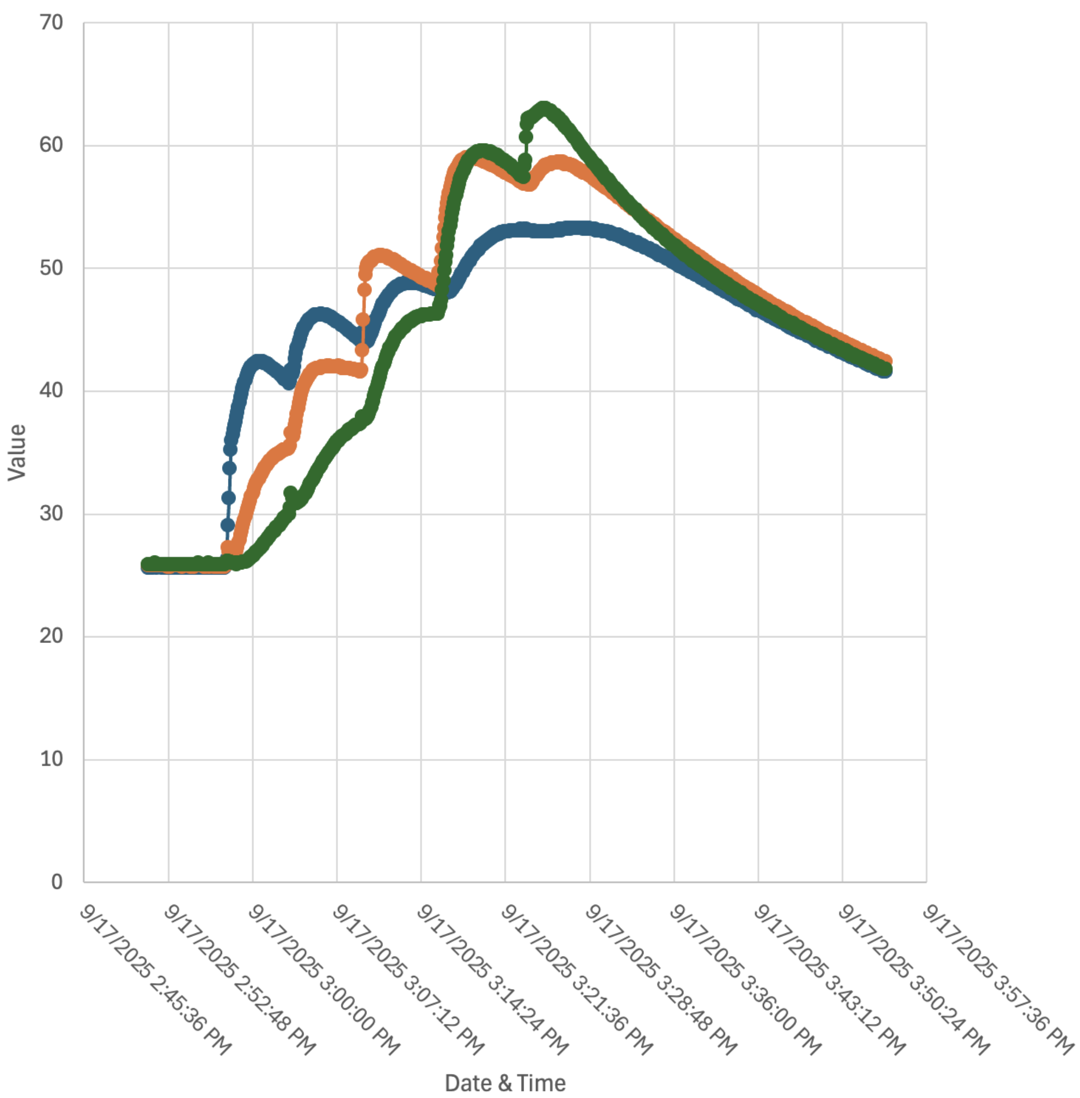
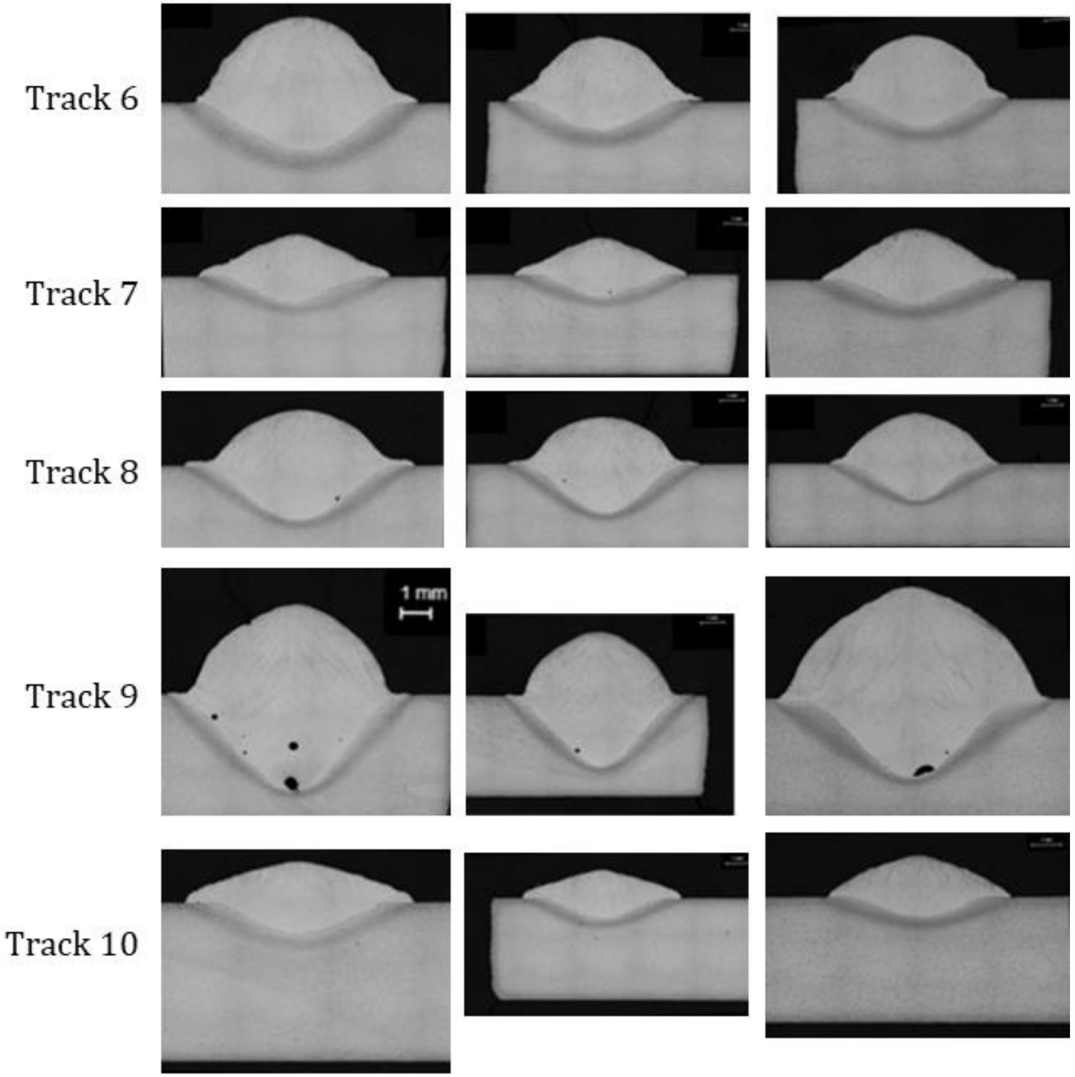
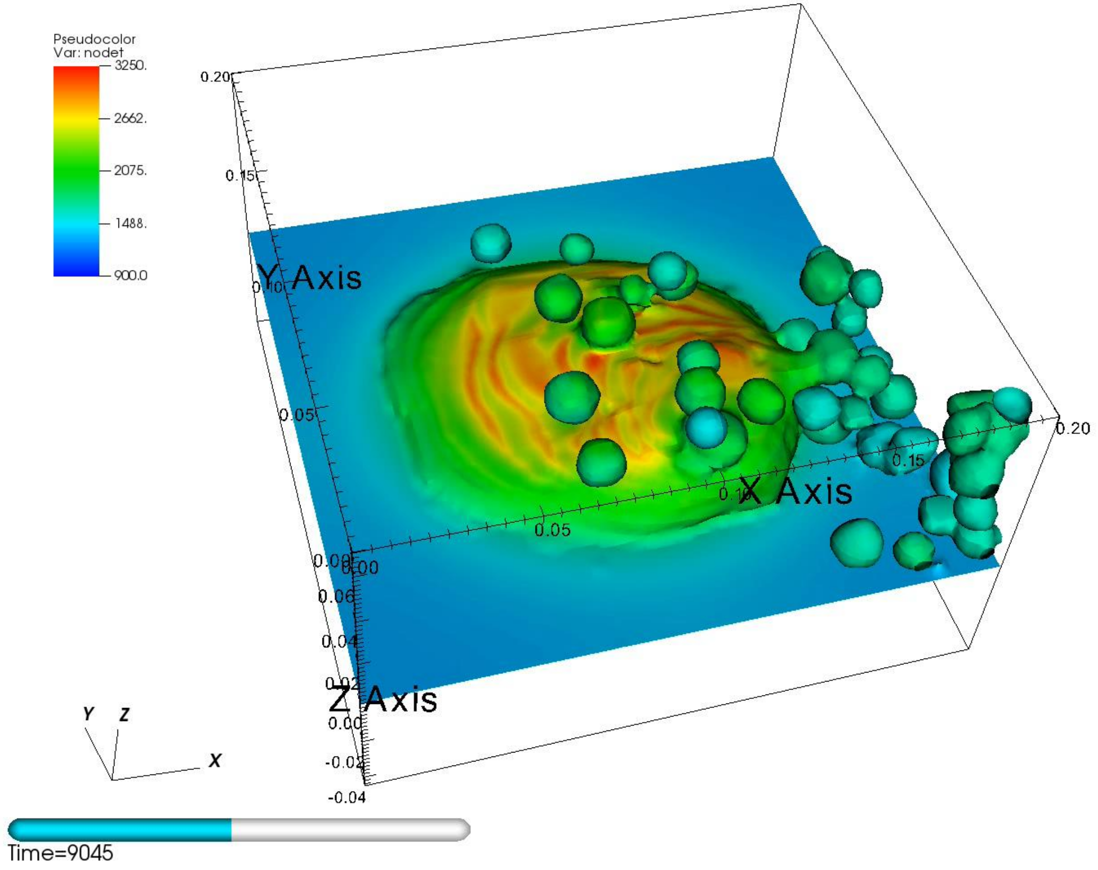
8-22 mm/s travel speed, 400-600 ipm wire feed rate, robot error for Beads 4-5

We extracted temperature data from three thermocouples and did ex-situ bead geometry characterization



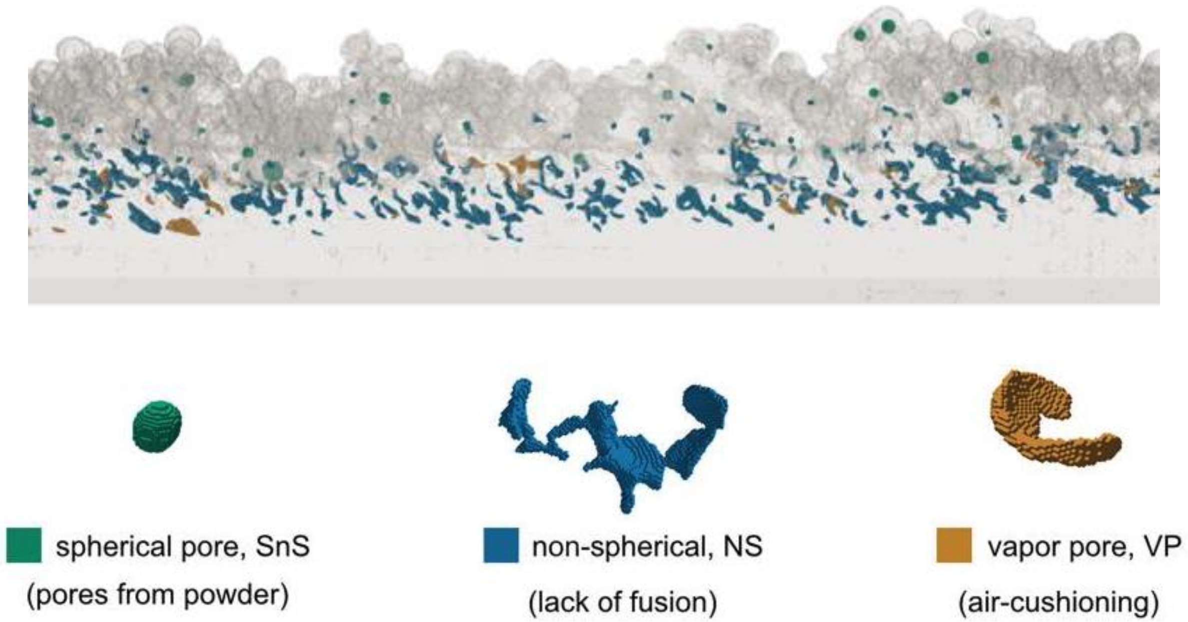


We use LLNL's highly utilized ALE3D code to study the detailed bead geometry, leveraging past success for laser-powder DED

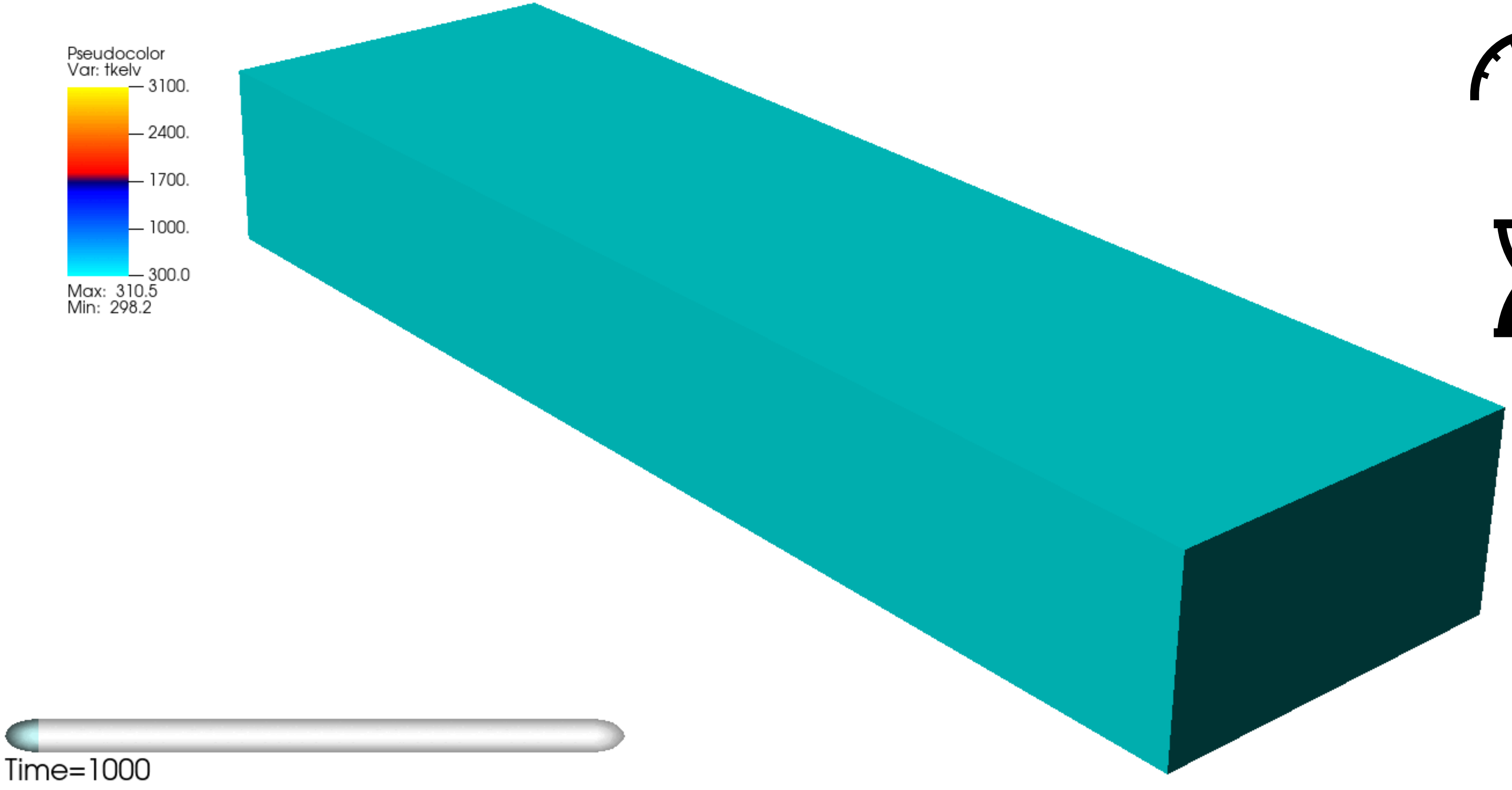


Khairallah, Additive Manufacturing 73 (2023) 103684

Weber et al, PNAS Vol 2, 1-9 (2023)



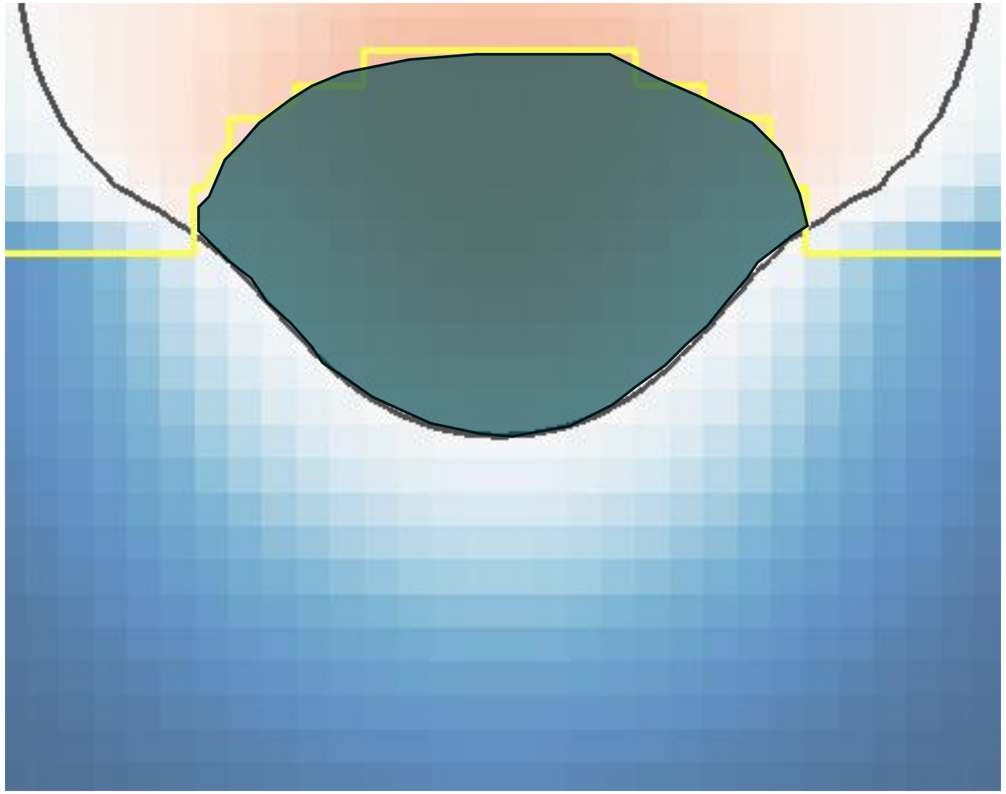
We calibrate ALE3D to reproduce the WAAM bead geometry in the experiments



- Melt pool depth
- Arc penetration
  New material temperature
- 36-108 minutes per simulation

Calibrating each print condition separately, simulations matched experiments within measurement uncertainty

2.61 mm



2.61 mm

Transitioning to the component scale, we use ORNL's open-source Adamantine code

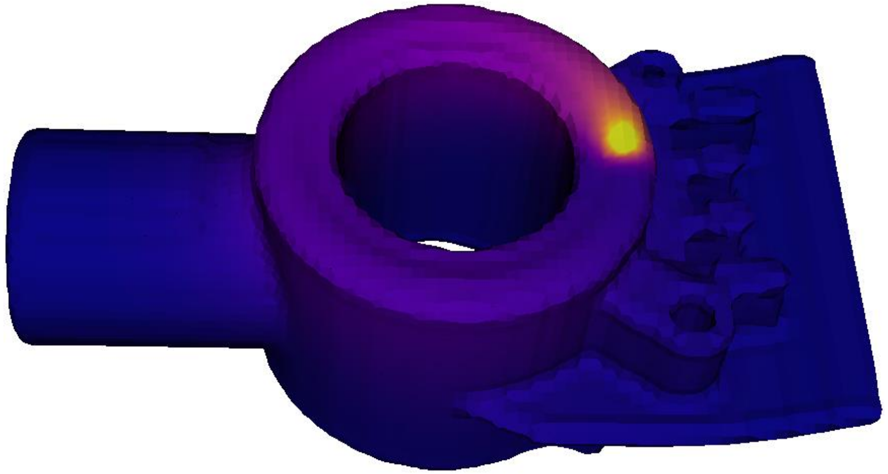
Built on **scalable, GPU-capable** libraries: deal.II, Kokkos, Trilinos, ArborX

Up to **10x faster than real-time** for thermal simulations

Adamantine *and its key dependencies* developed at ORNL, **we can modify and integrate at-will**

Integrated into the MDF digital ecosystem

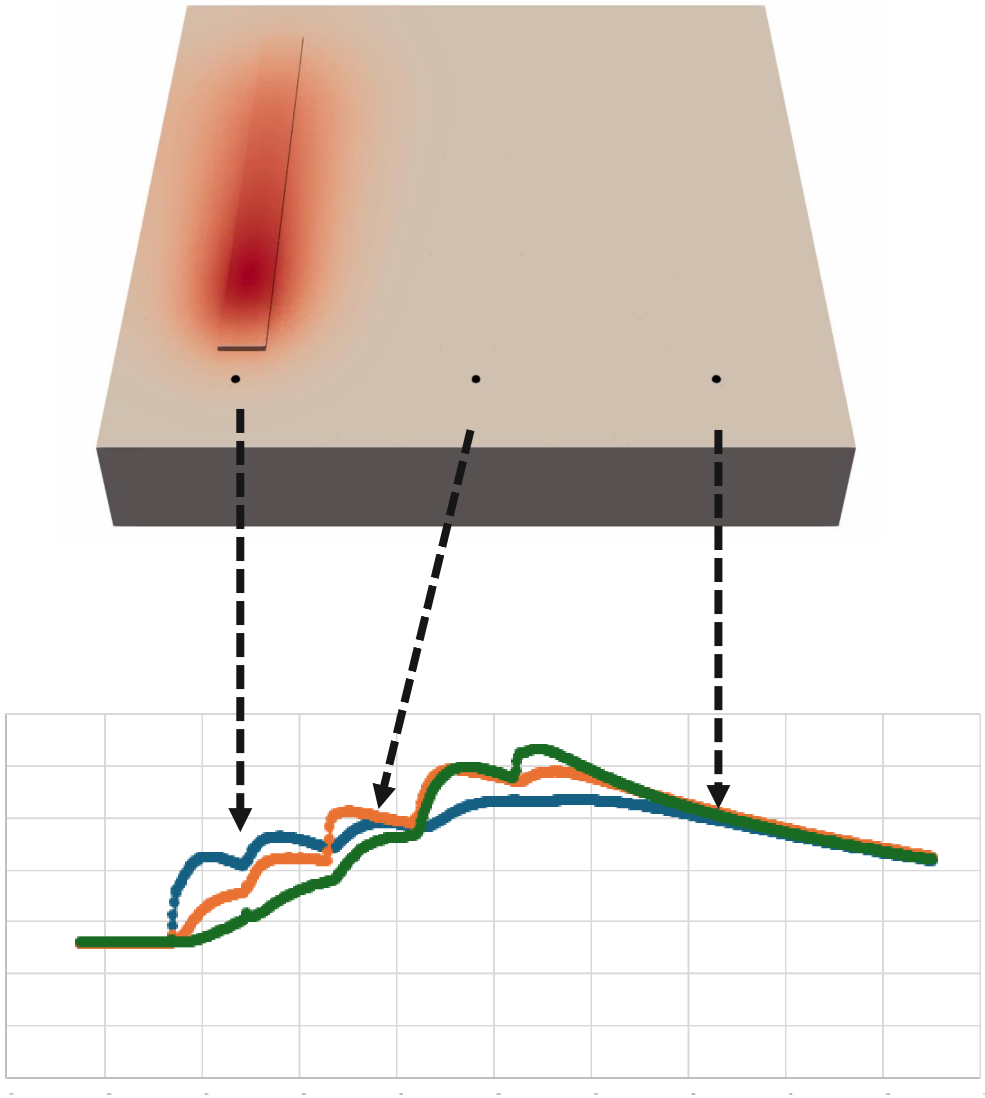
ADAMANTINE



https://github.com/adamantine-sim/adamantine

B. Turcksin, S. DeWitt, Journal of Open Source Software, 9 (102), 2024.

We use a two-stage process to calibrate Adamantine, starting with macroscale heat input/output from the thermocouples

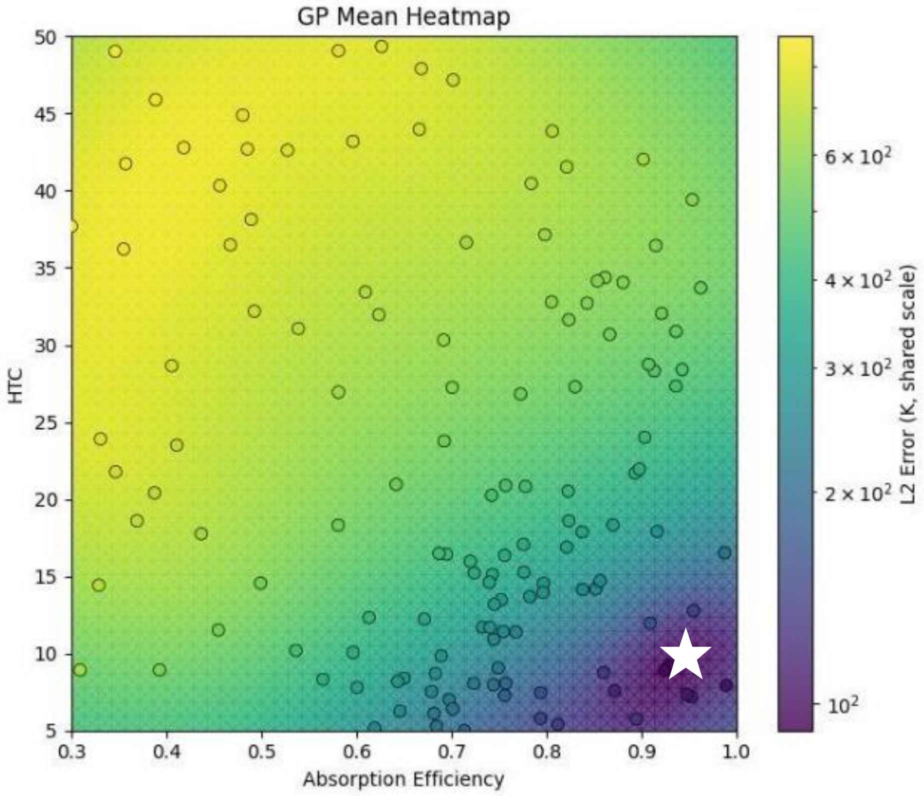


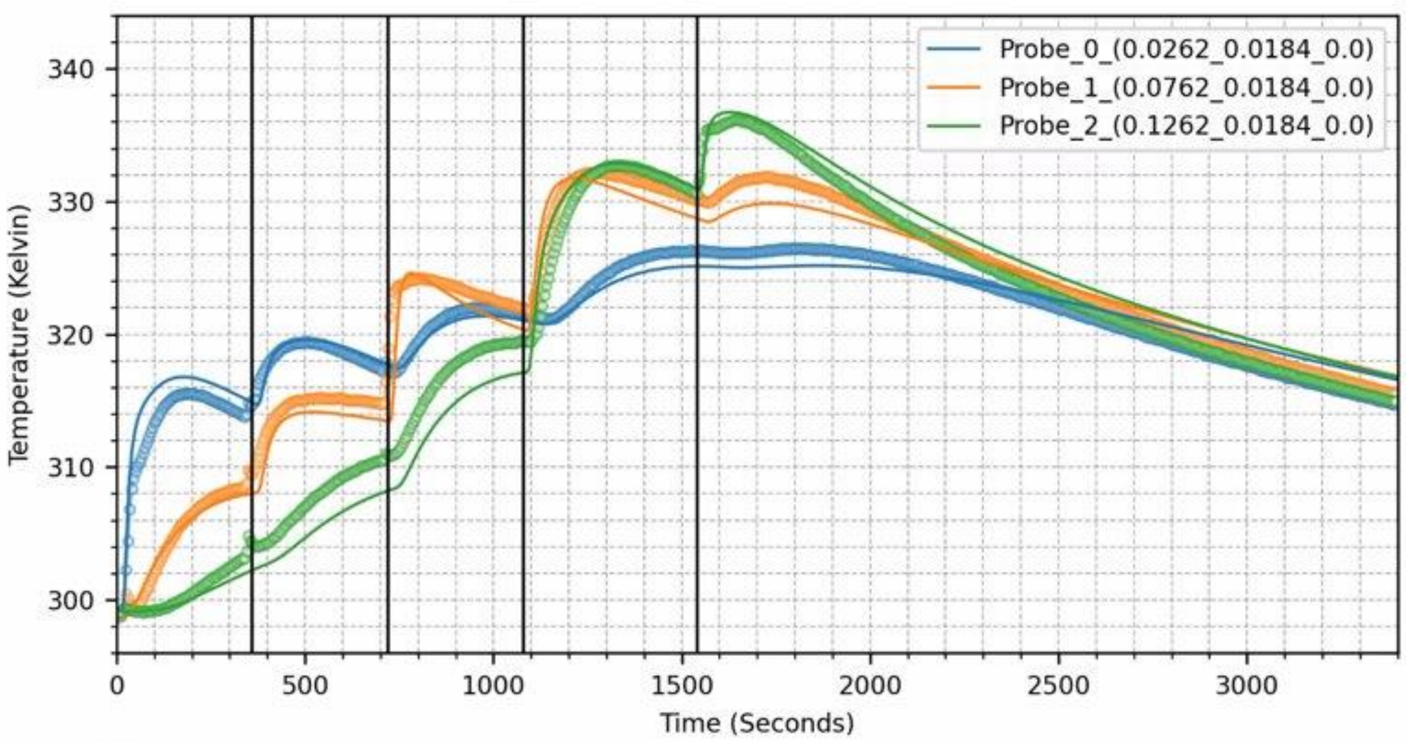
Thermocouple time series

Heat source efficiency
Convective cooling

< 2 hours per simulation on 8 CPU cores

We found a consistent calibration across the beads despite the coarse simulation geometry





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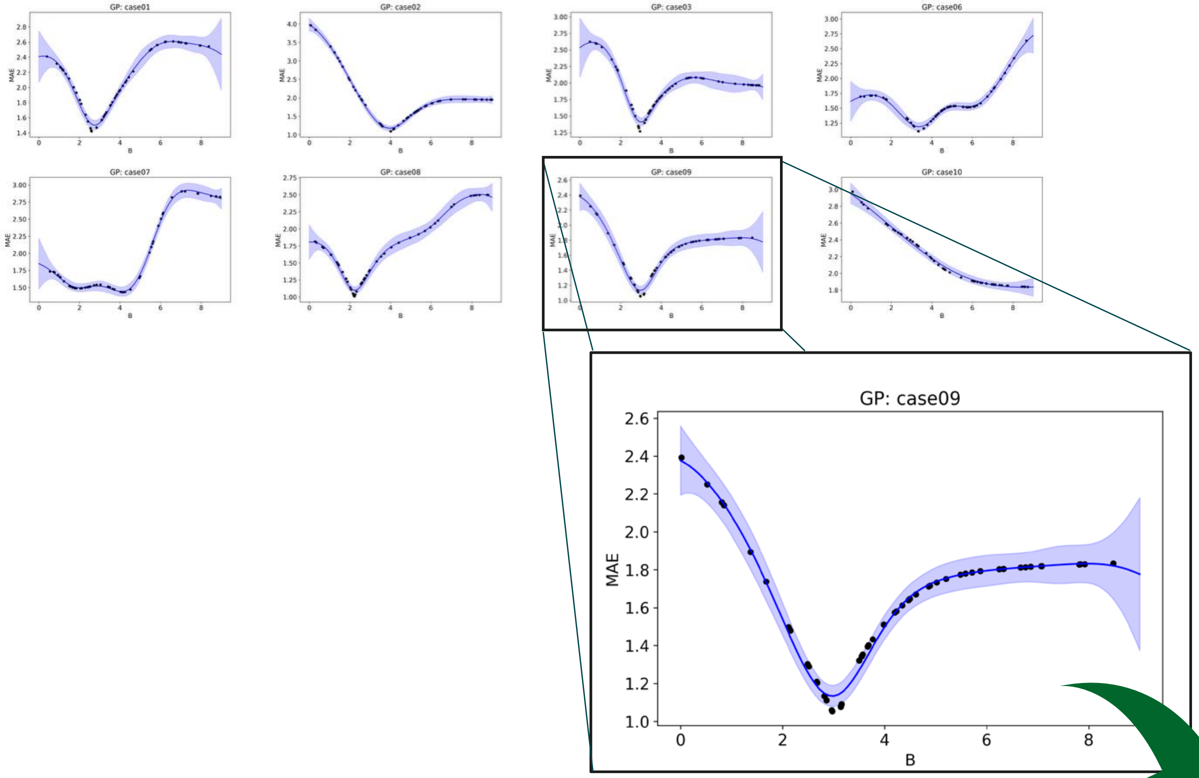
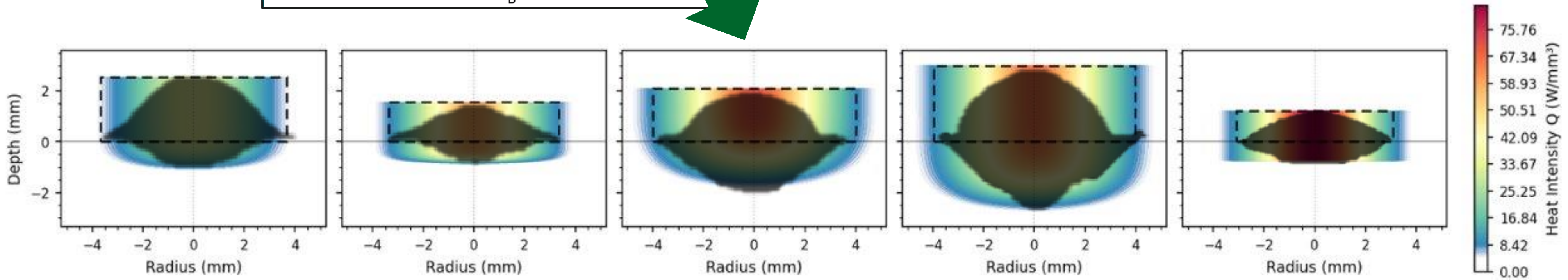
In the second calibration stage, we calibrate the heat source shape for each printing condition



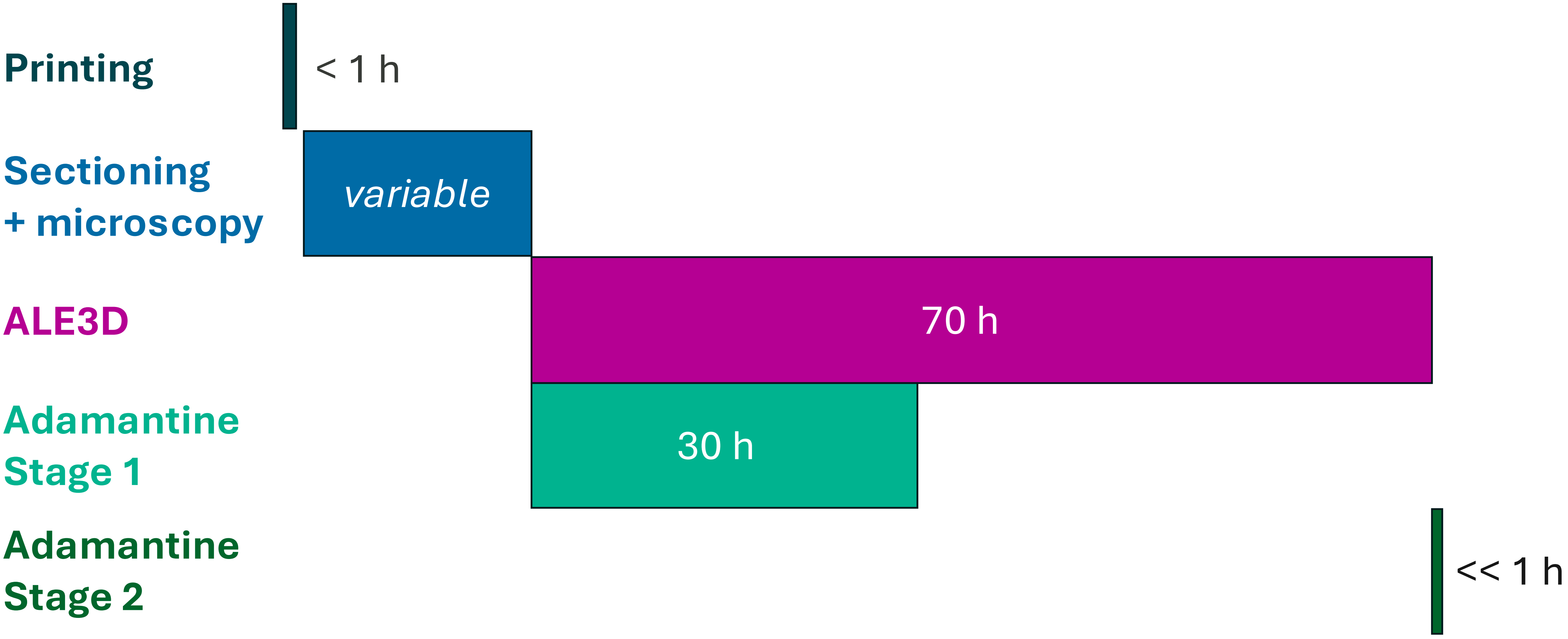
ALE3D temperature
Experimental depth

Heat source shape parameter

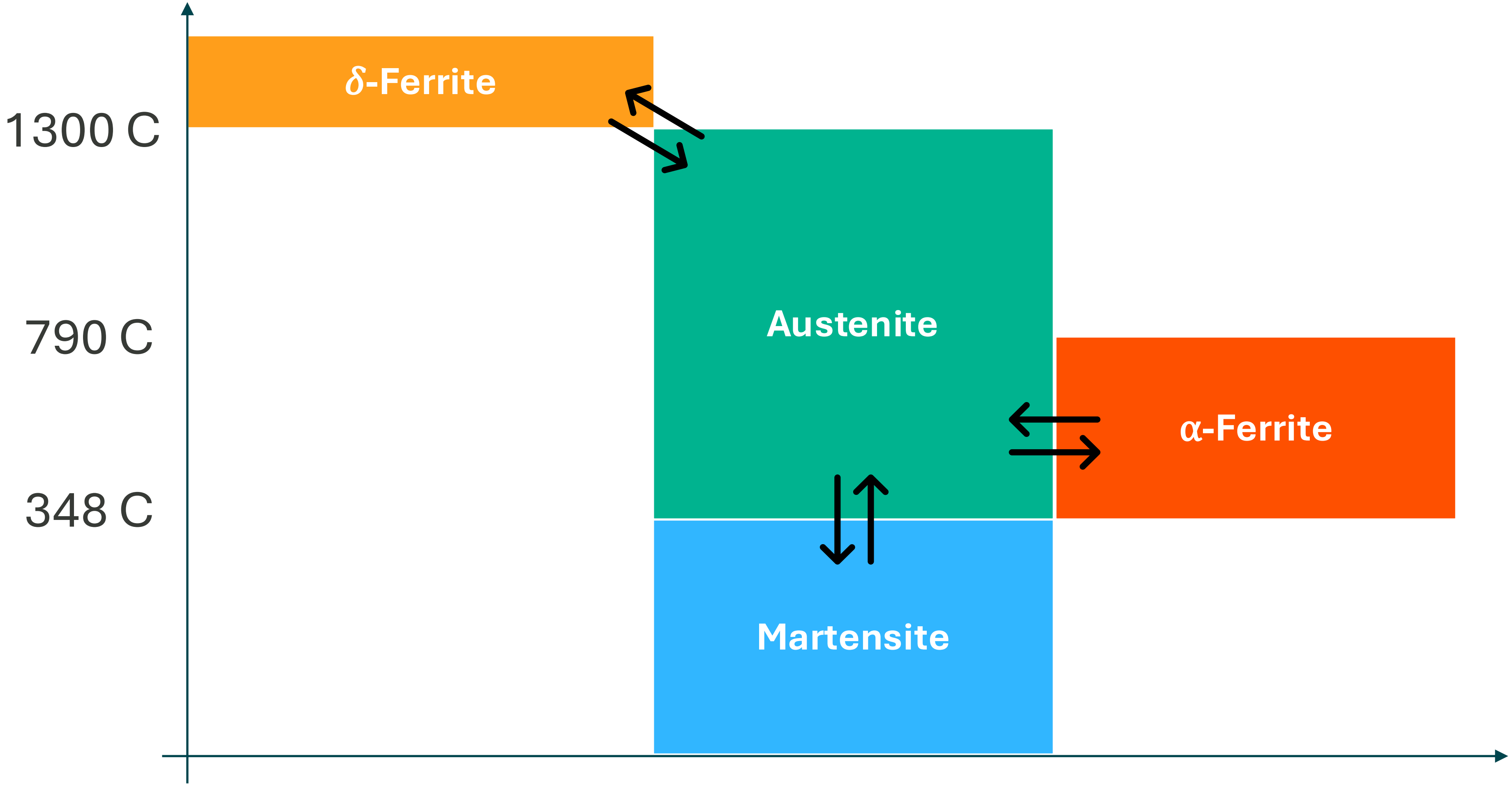
<1 second per simulation



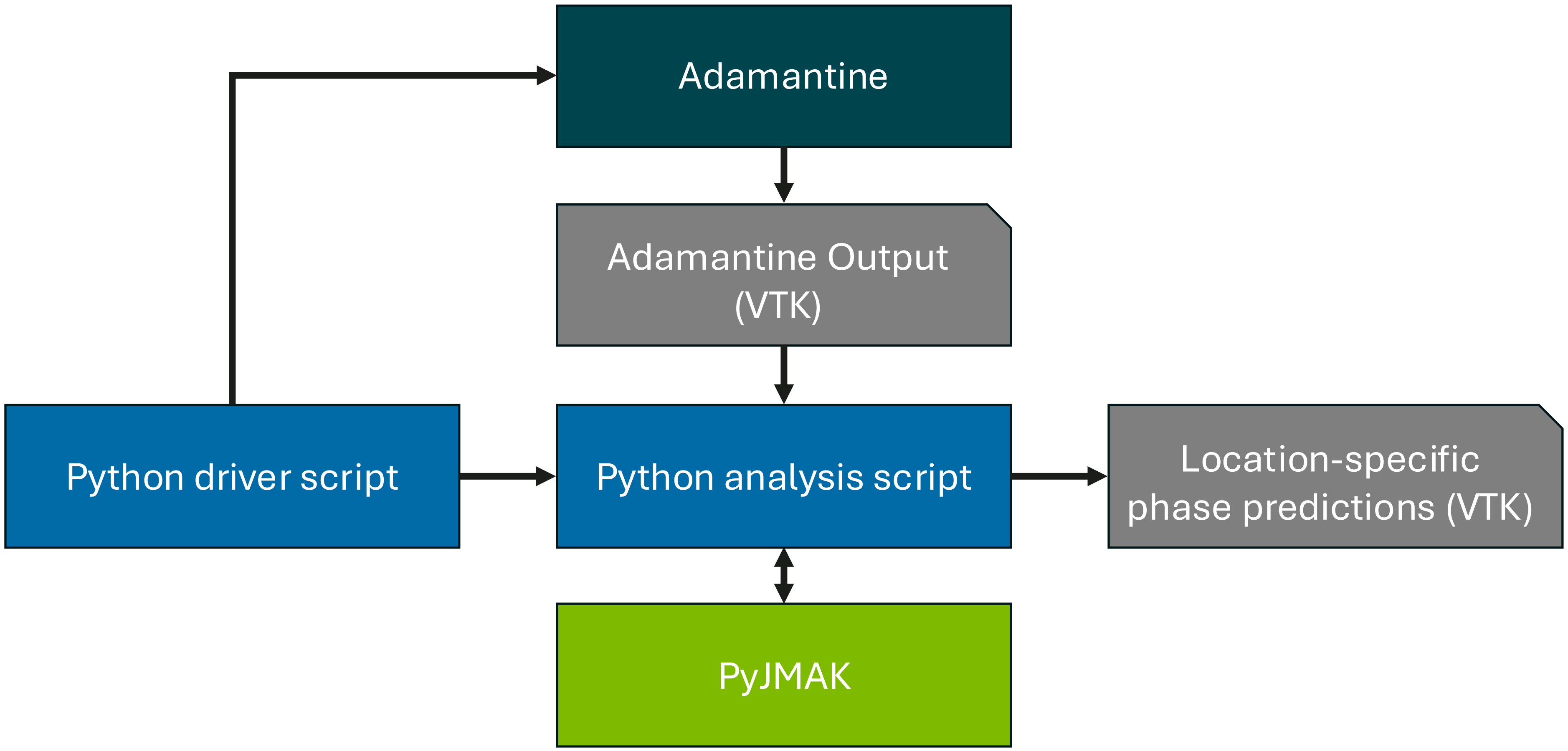
Overall, this calibration pipeline takes about 3 days of mostly passive time (neglecting sectioning and microscopy)



With Adamantine calibrated, next we predict the complex phase transformations in 410NiMo stainless steel



To predict this phase evolution, we use ORNL's PyJMAK code with file-based coupling to Adamantine



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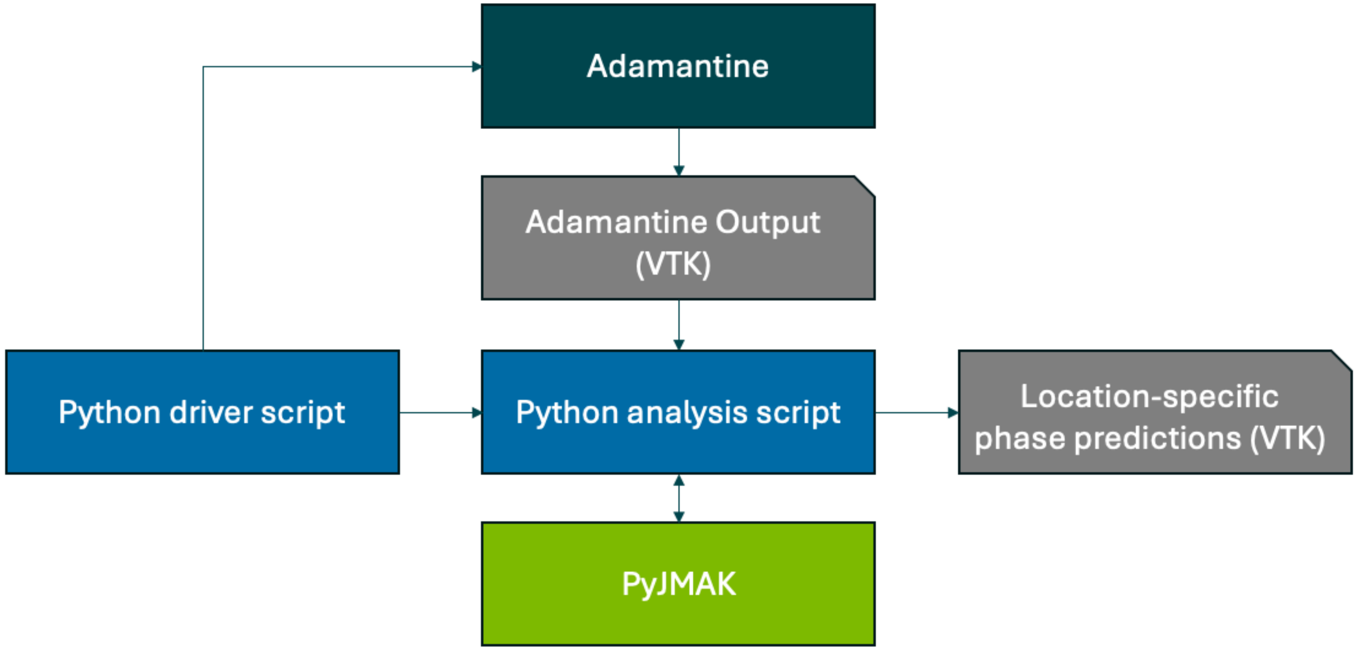
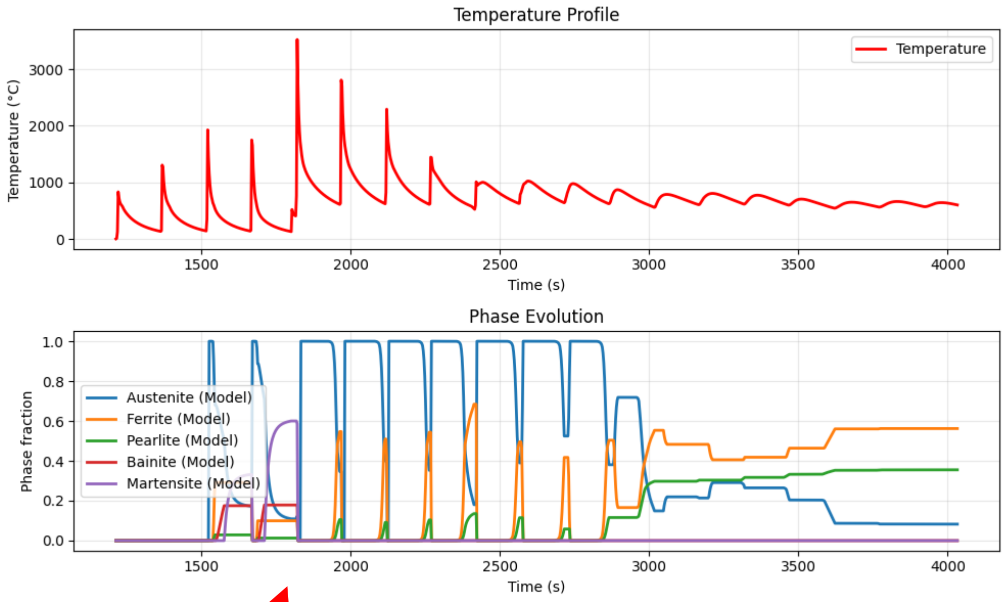
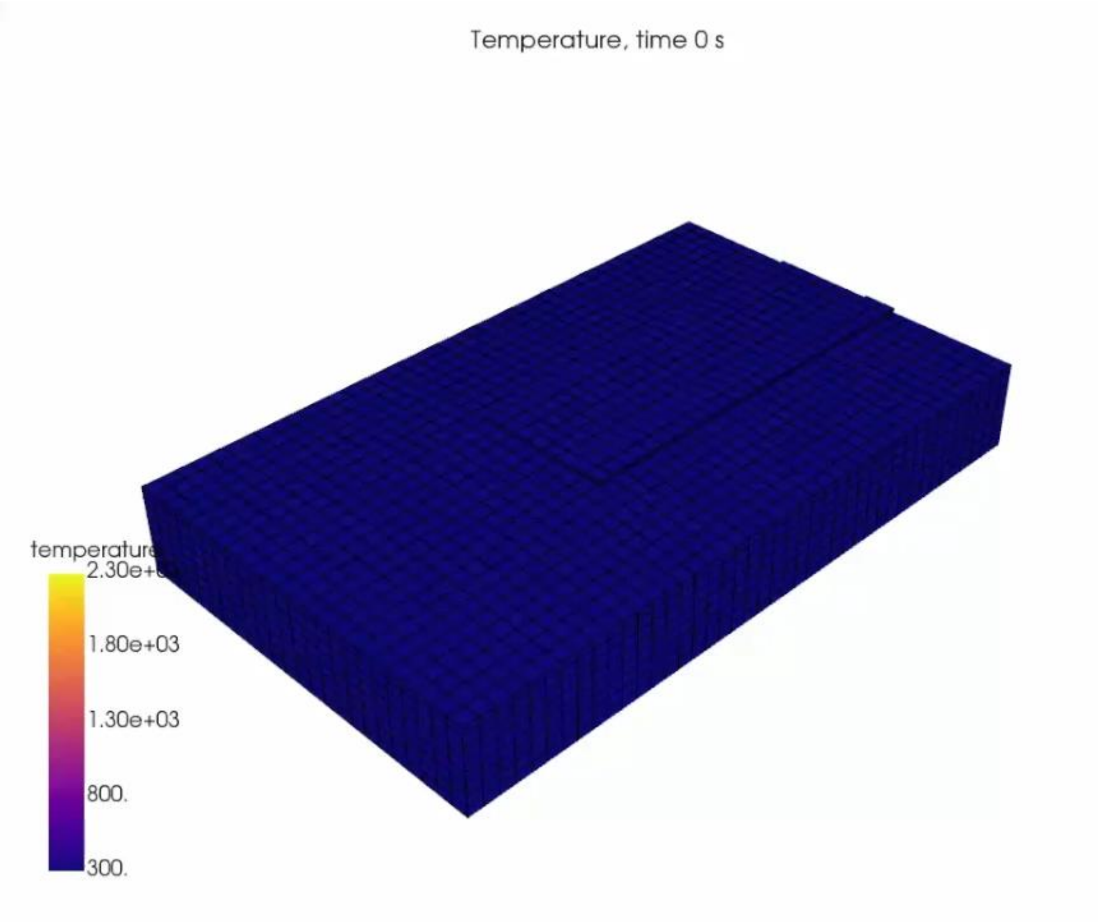
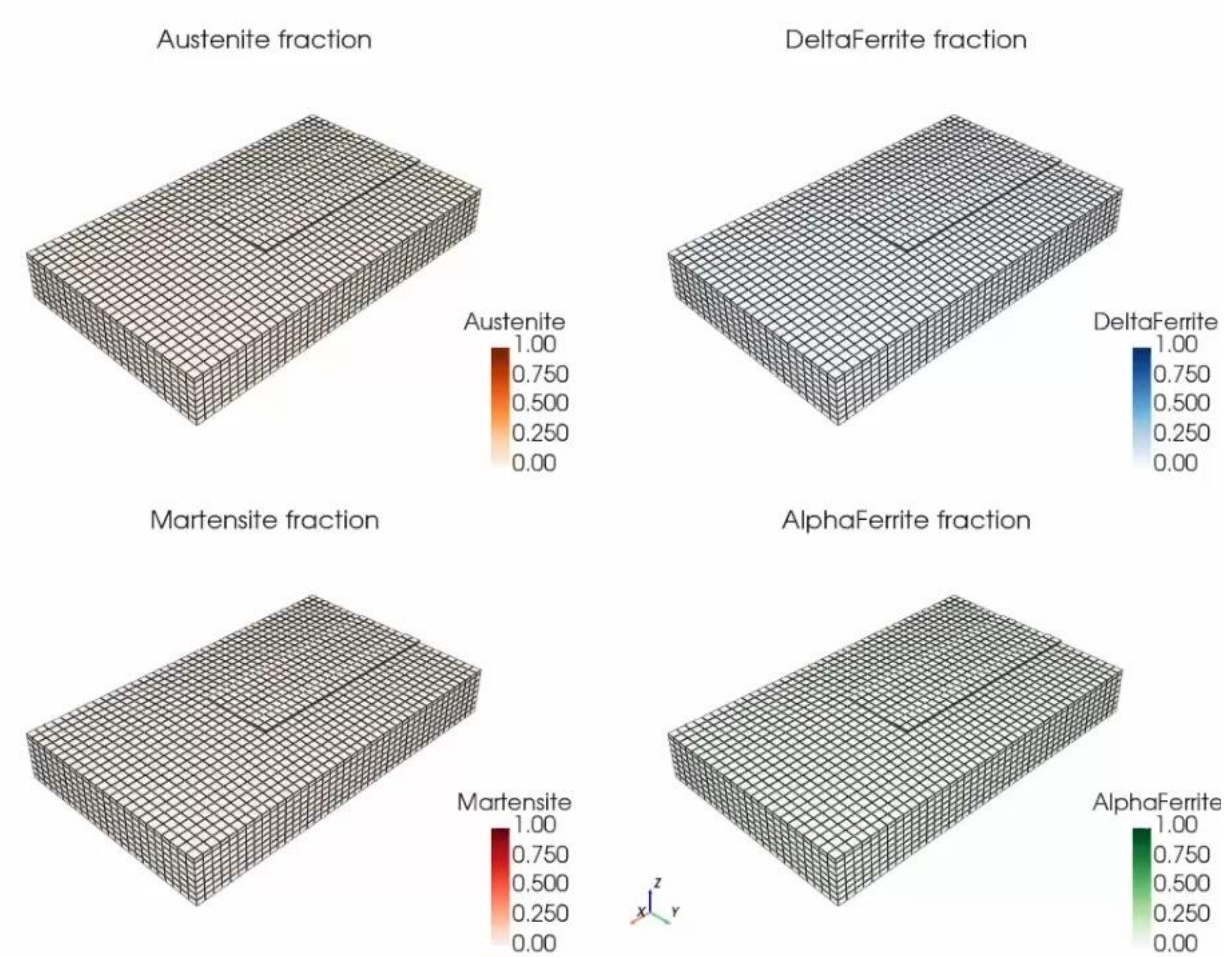


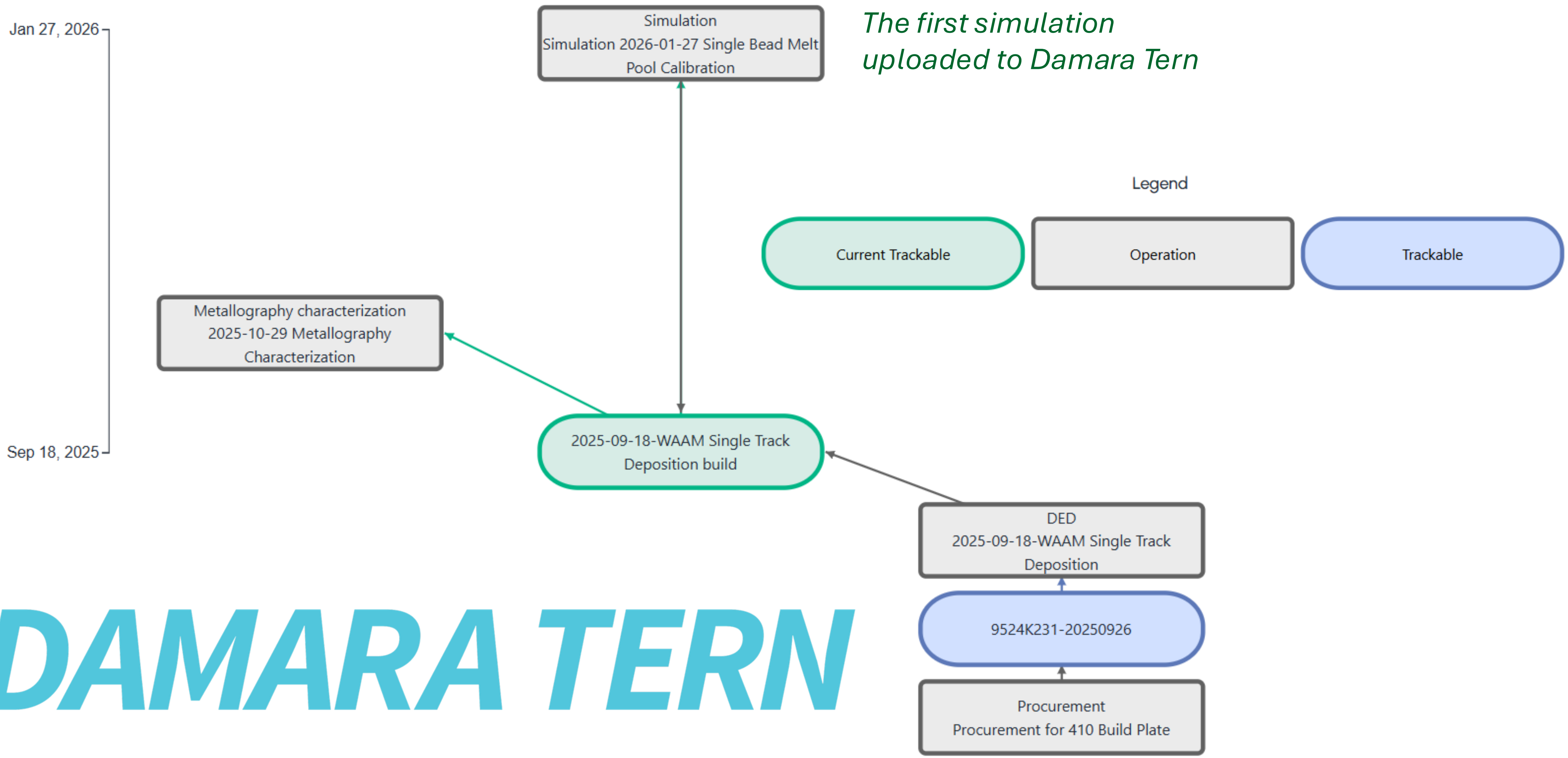


With the HPC4MDF framework, we can predict the phase fractions for the RUNNERS T-joint, with validation underway





Throughout this workflow, we track the steps and data using the Damara Tern, the MDF's federated data platform

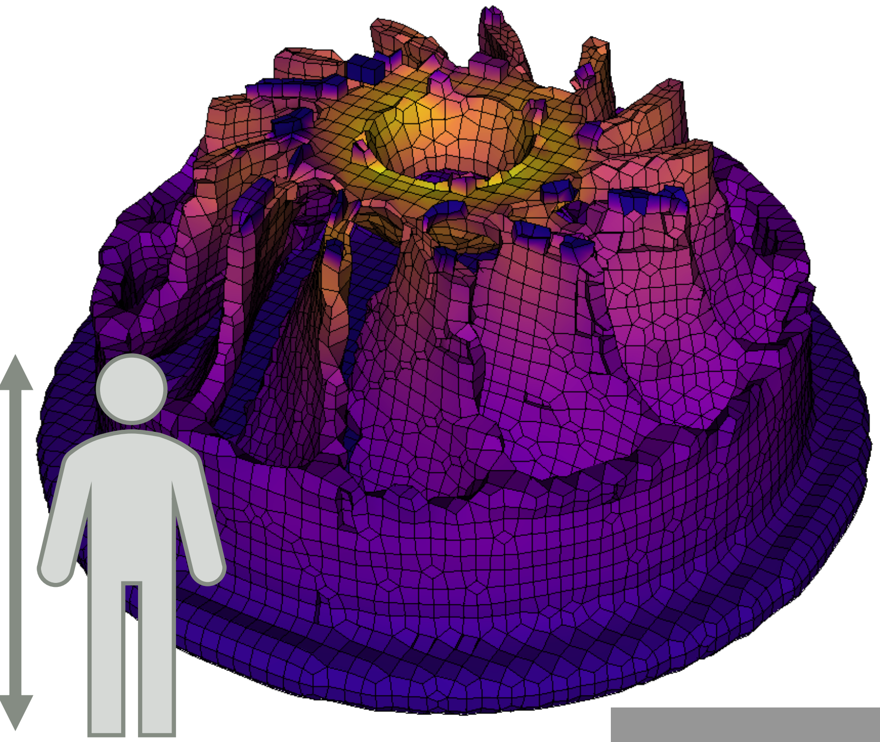


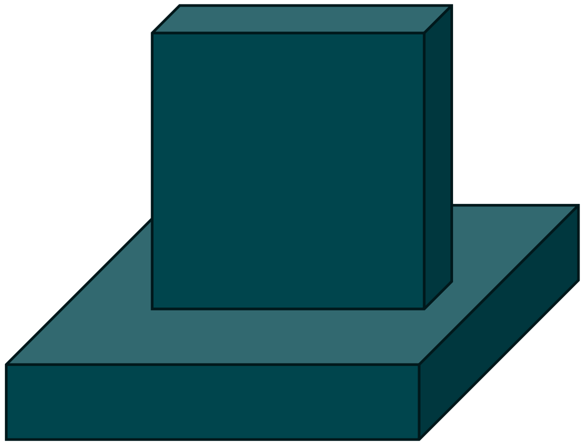
The first simulation uploaded to Damara Tern

DAMARA TERN

With this new capability in place, we’re ready to apply it and extend it further

We are currently using the framework to evaluate how representative qualification artifacts are of a full-size runner





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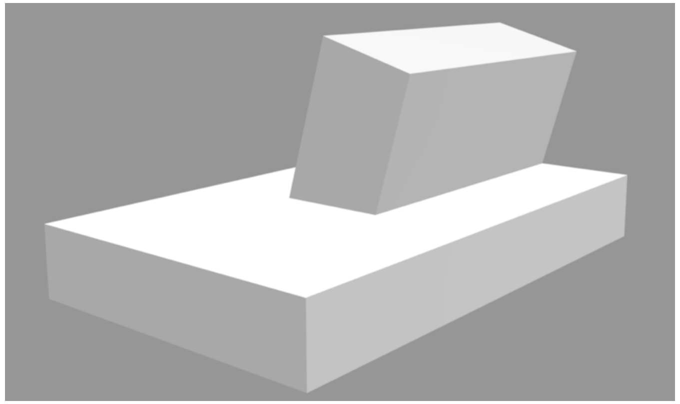
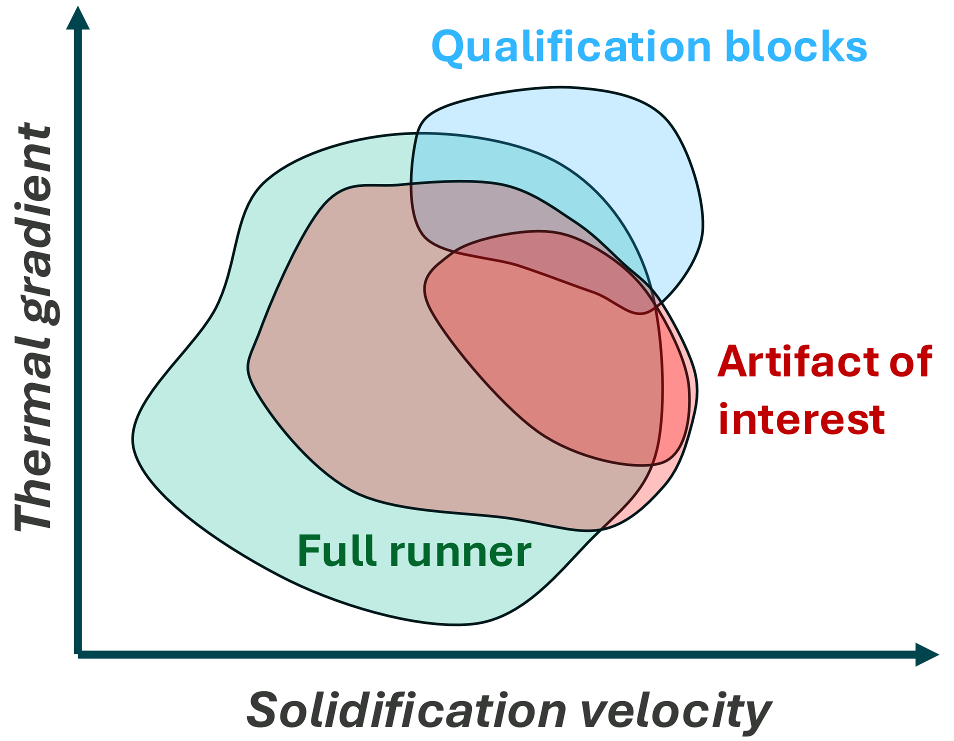
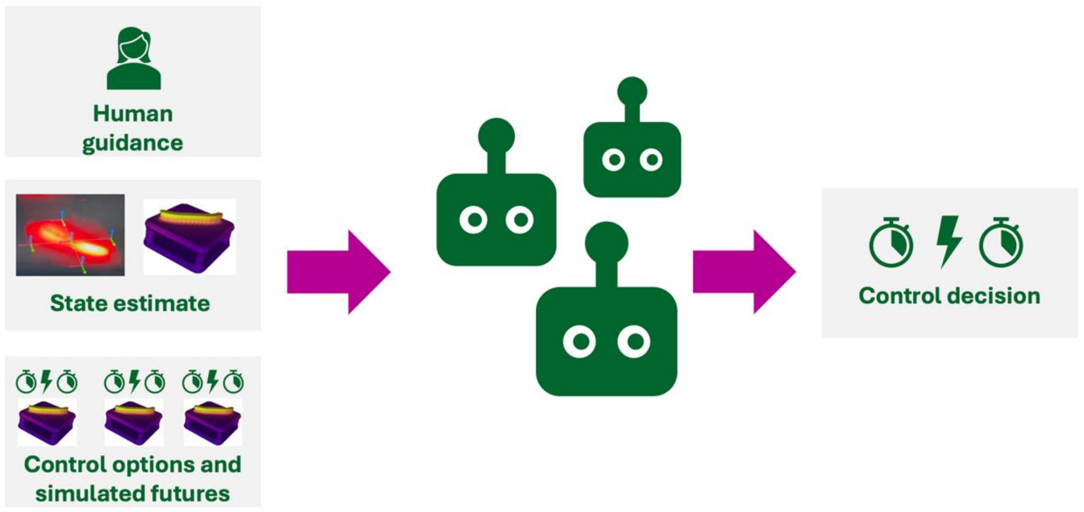




The HPC4MDF framework can be integrated into agentic workflows at the MDF, where Adamantine plays a central role



LOOP: Agent-in-the-loop adaptive control of additive manufacturing

Genesis Mission

Autonomously Designed

Autonomously Manufactured and Constructed

Autonomously Generated Regulatory Documents

Autonomously Operated

PROMETHEUS: Delivering nuclear energy that is faster, safer, cheaper

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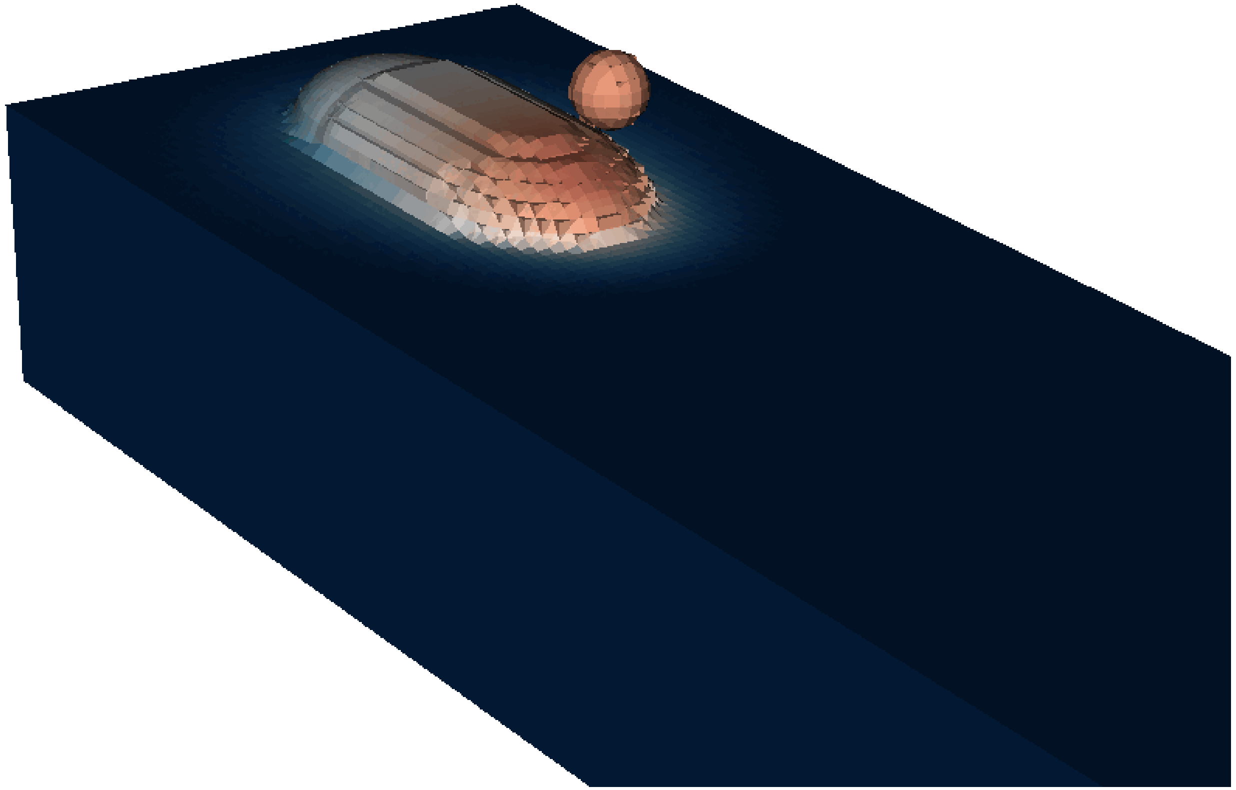
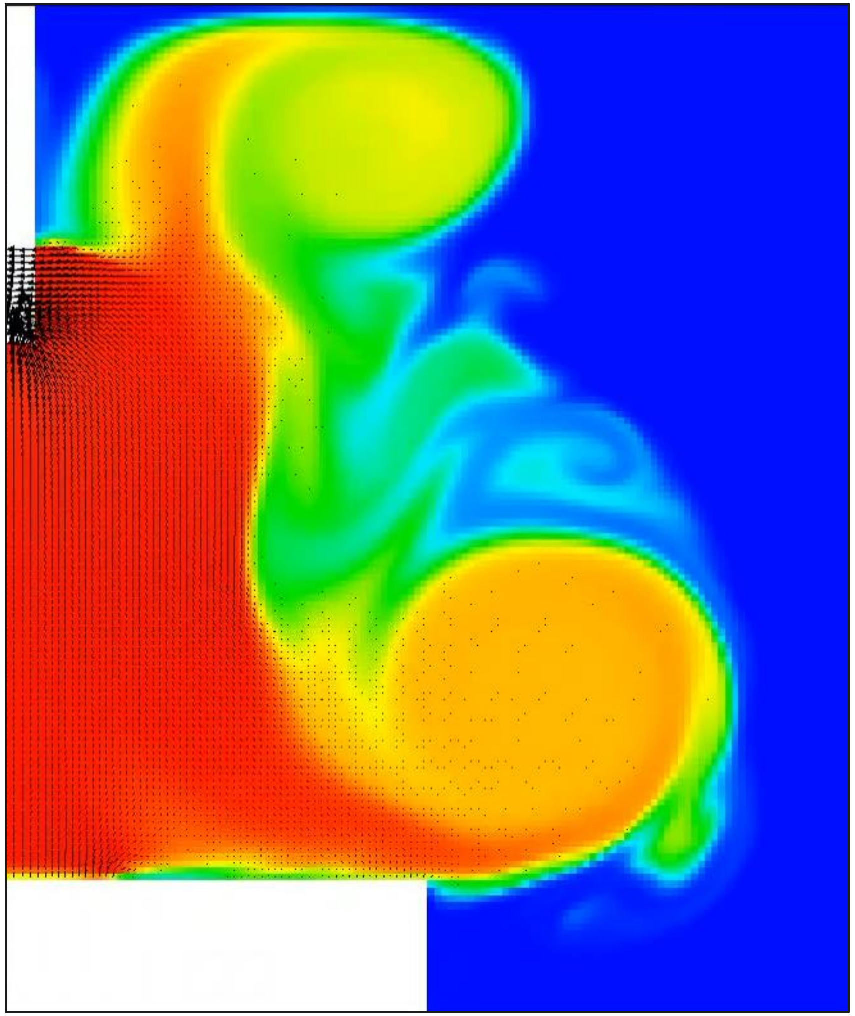
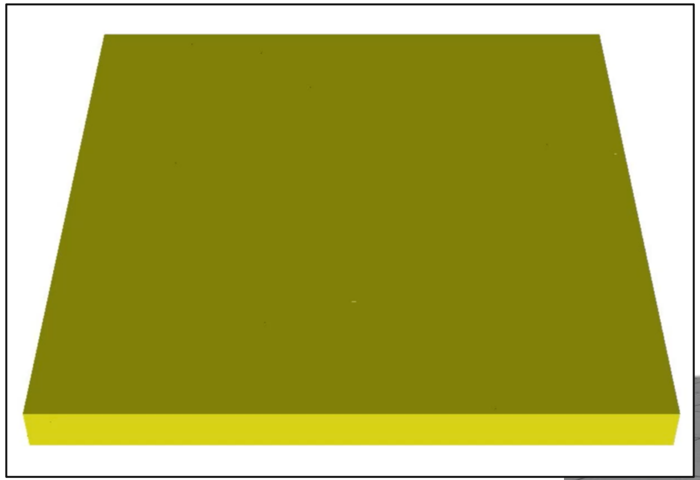
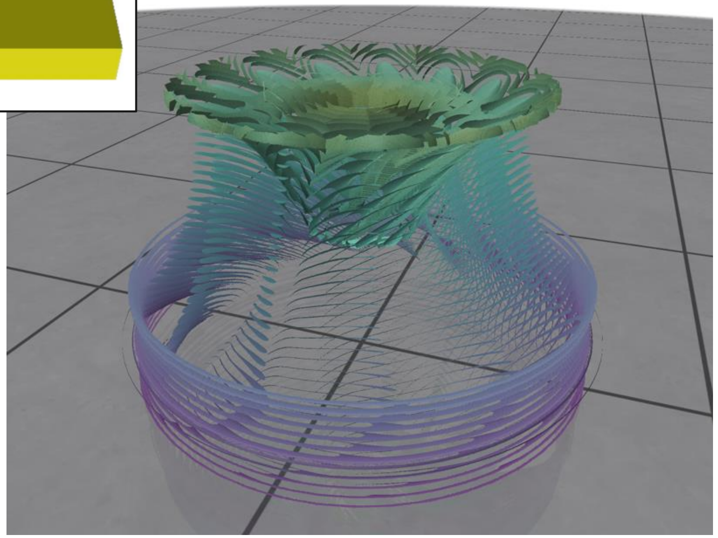
Moving beyond thermal simulations, the team is investigating hydrodynamics and plasma simulations with ALE3D





In HPC4MDF we are adding initial support for 5-axis in Adamantine, but toolpath generation remains a research topic





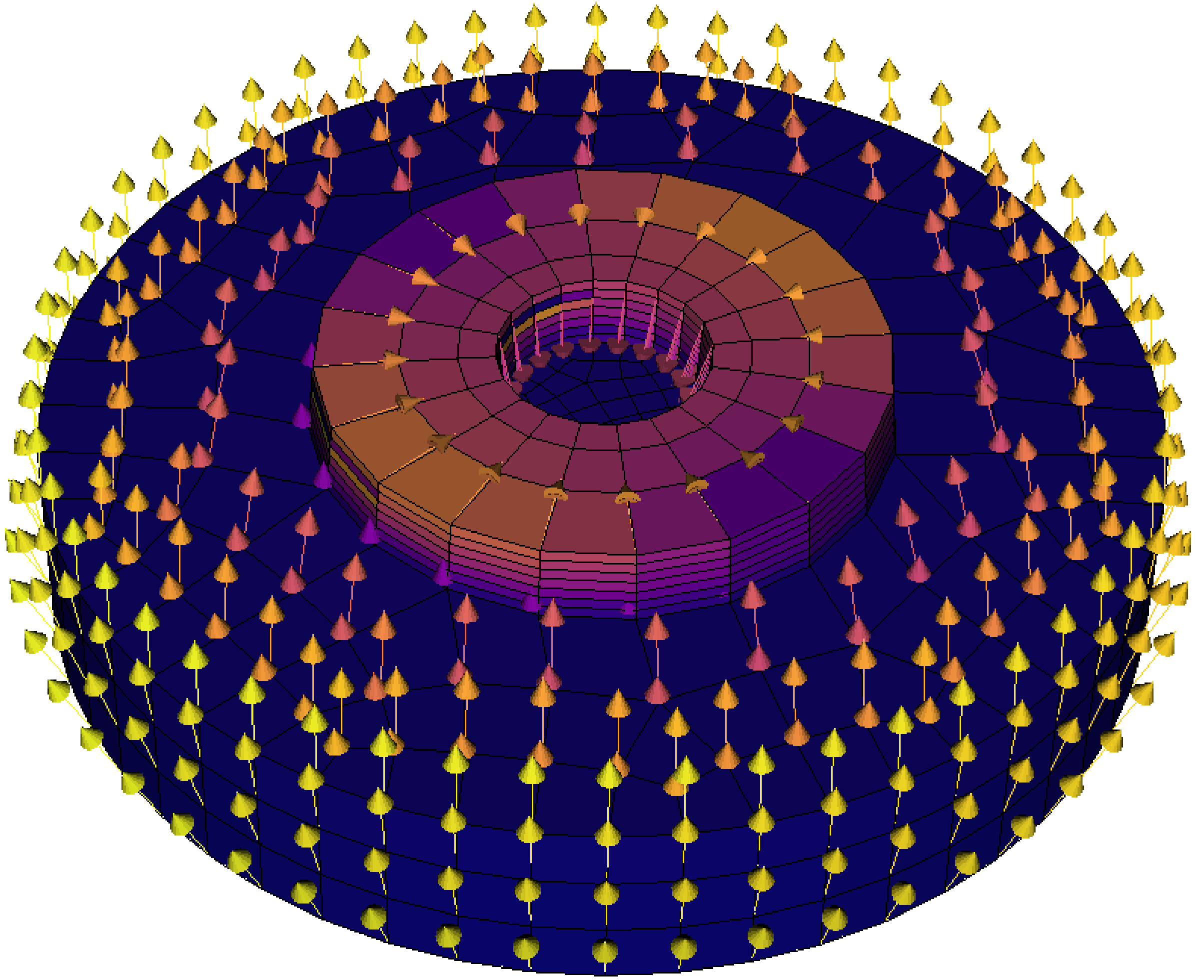
Courtesy of Liam White (ORNL)

Quaternion-based heat source added to Adamantine

Currently limited to rotations while the welder is off

Level-set-based methods are a promising path forward for generating toolpaths

In HPC4MDF we are adding initial support for GPU thermoplasticity in Adamantine for distortion/residual stress

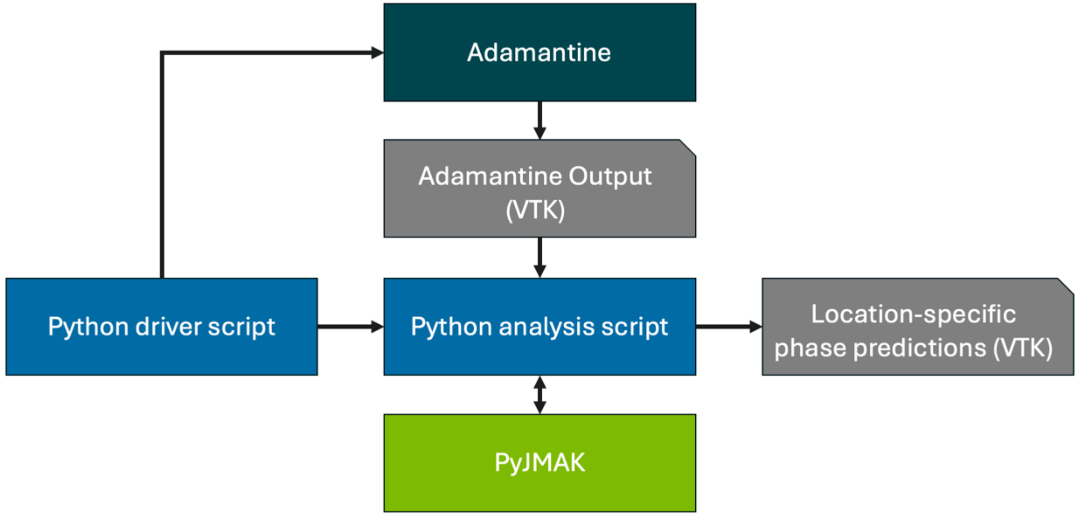


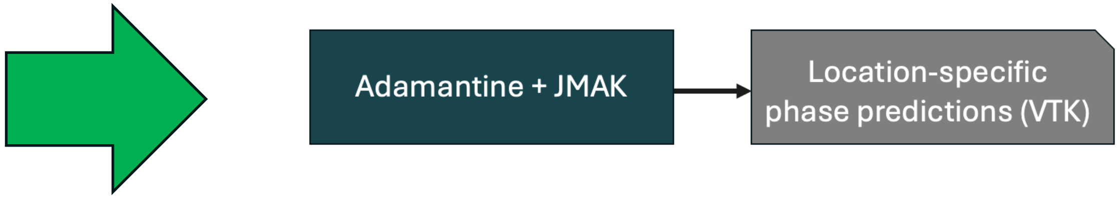
GPU-accelerated simulations running on OLCF Frontier

Currently infinitesimal strain and simple constitutive laws

Need finite strain and more complex constitutive laws

The downsides for file-based coupling of Adamantine and PyJMAK motivate tighter integration in the future





Non-intrusive*, but *slow with extra bookkeeping

Microstructure effects on mechanics impossible

Intrusive*, but *fast

Microstructure effects on mechanics possible

To move US industry forward, we want to make these capabilities available to the broader community

Component-level simulations: Adamantine
Open Source: *https://github.com/adamantine-sim/adamantine*

ADAMANTINE

Bead-level simulations: ALE3D

Export controlled
Cloud version being investigated (ALE3D4I)

Calibration framework: Dial
Open source: *https://github.com/INTERSECT-DIAL/dial*

Dial

Distributed INTERSECT Active Learning

Phase prediction: PyJMAK

Open-source release in progress

Additional resources

https://github.com/adamantine-sim/adamantine-tutorials
https://github.com/adamantine-sim/adamantine-utils
https://github.com/adamantine-sim/workflow-scripts

- Summer 2026
- Expanding to a 3-day event
- Covering tools for:
  - Laser processing
  - Large-scale AM
  - Microstructure evolution
  - Coupled workflows
  - ...and more!

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In summary, the new HPC4MDF smart manufacturing platform:

1) **Provides critical capabilities** for US industry, integrated into the MDF ecosystem
2) **Serves as an insertion point** to test new computational approaches going forward
3) **Derisks development** for commercial codes