# *Part-Level Finite Element Simulation of Selective Laser Melting*

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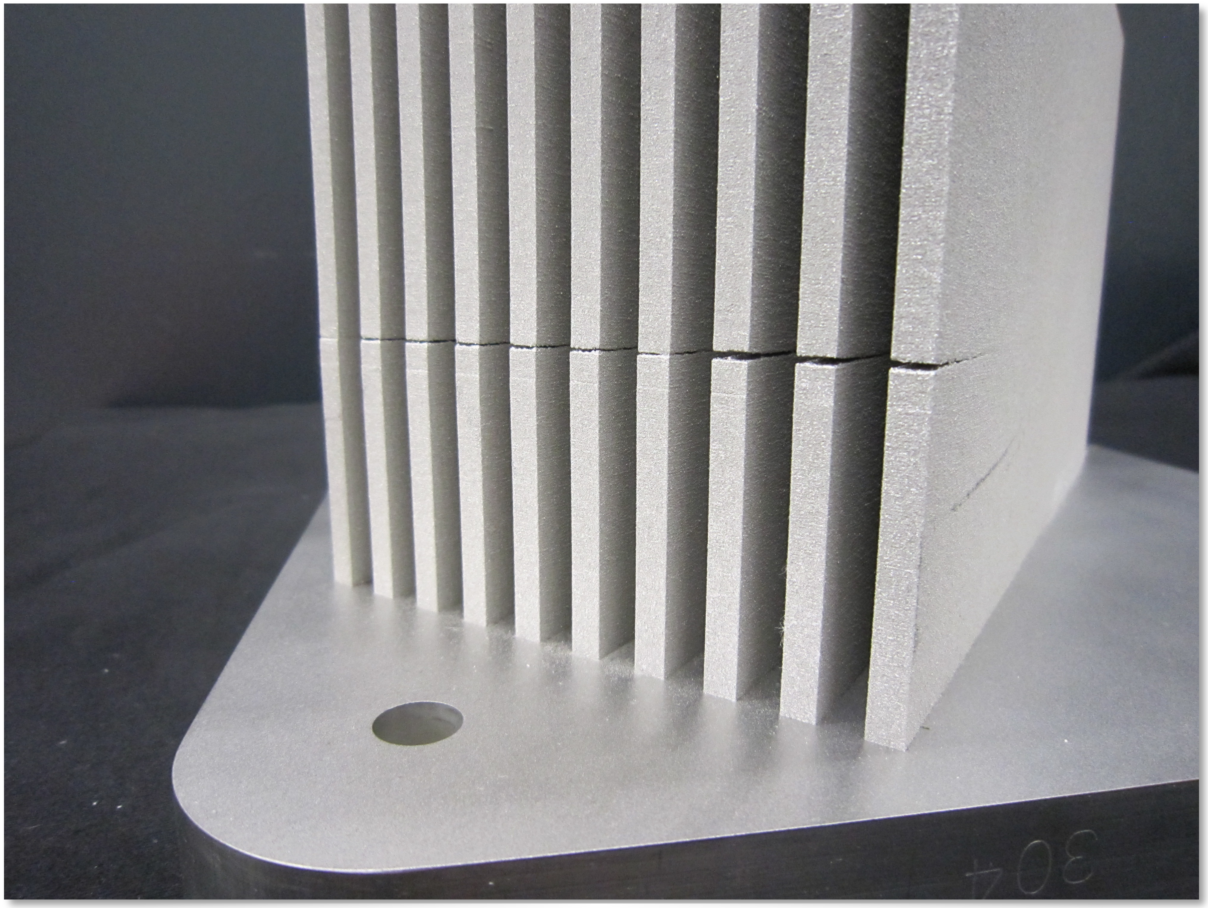
# Selective Laser Melting AM has great potential *and* challenges




In-machine failure during 316L fabrication at LLNL

Part-scale modeling is needed to inform part-specific configurations and processes

# Our Diablo code is being used to solve the multi-physics problem

- Balance of thermal energy

$$\rho c\dot{T} = -\mathrm{div}\ \mathbf{q} + r$$

- Associated thermal moving boundary problem

$$\left(\mathbf{k}_1 \frac{\partial T_1}{\partial \mathbf{x}} - \mathbf{k}_2 \frac{\partial T_2}{\partial \mathbf{x}}\right) \bullet \mathbf{n} = H\rho \frac{\partial \mathbf{x}_p}{\partial t} \bullet \mathbf{n}$$

- Balance of linear momentum

$$\rho \ddot{\mathbf{u}} = \mathrm{div}\ \mathbf{T} + \rho \mathbf{b}$$

- Highly parallelized, implicit FE, *staggered* or BFGS

Base capability has been exercised extensively

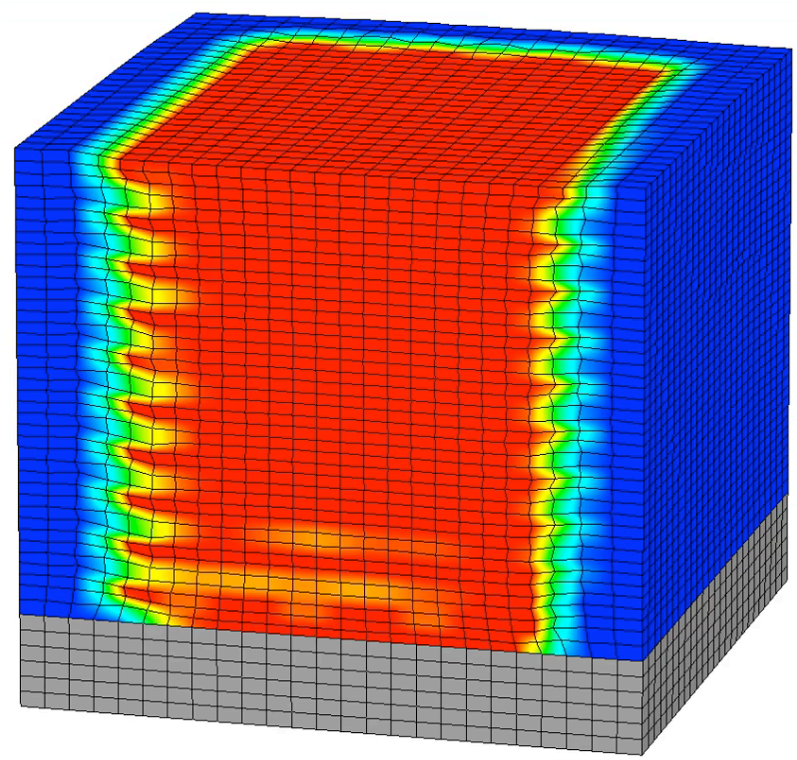
# Diablo is being extended with features for modeling SLM

- Successive activation of mesh regions
- General laser path input definition
- Solid-only representation
- Powder as a low-strength solid
- Powder-to-solid as an irreversible phase transformation

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_u + \boldsymbol{\varepsilon}_T + \boldsymbol{\varepsilon}_\phi$$

- Rule of mixtures response in partially transformed elements

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}(grad\,\boldsymbol{u}, T, \phi_1, \phi_2)$$

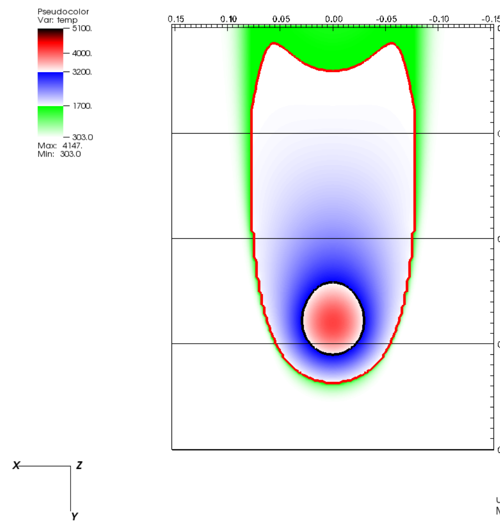


We started with simple modeling abstractions to evaluate their utility

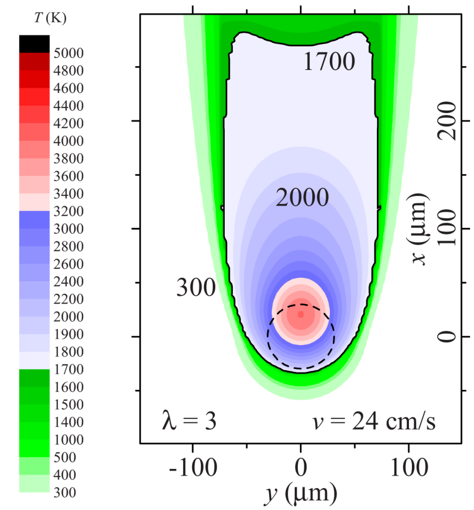
# Energy deposition model adopted from Gusarov *et al.* (2009)

$$r(\sqrt{x'^2 + y'^2}, z') = -\beta_h Q_0 \frac{\partial q}{\partial \xi'}$$

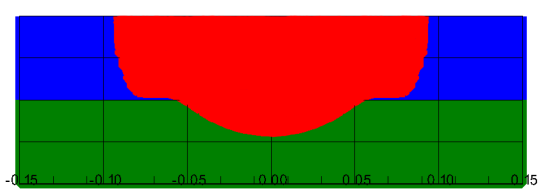
- Implementation verified against their published results
  - Melt pool footprint (right) @ 240 mm/sec
  - Melt pool profile (below) @ 120 mm/sec



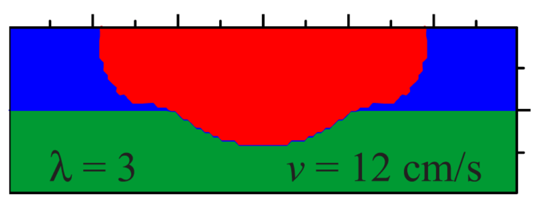

Diablo




Gusarov




Diablo



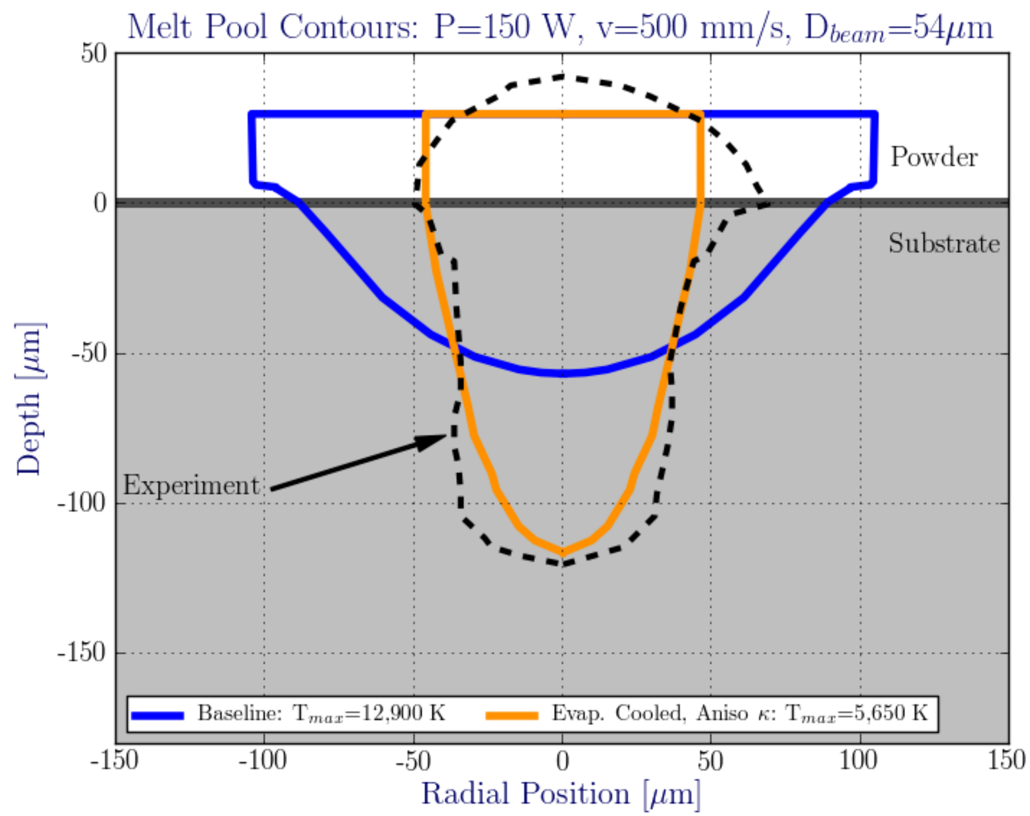

Gusarov

A. V. Gusarov, I. Yadroitsev, Ph. Bertrand, and I. Smurov, "Model of radiation and heat transfer in laser-powder interaction zone at selective laser melting," *Journal of Heat Transfer* **131**(7):072101, 2009.

Relies on a simple knock-down factor for other energy losses

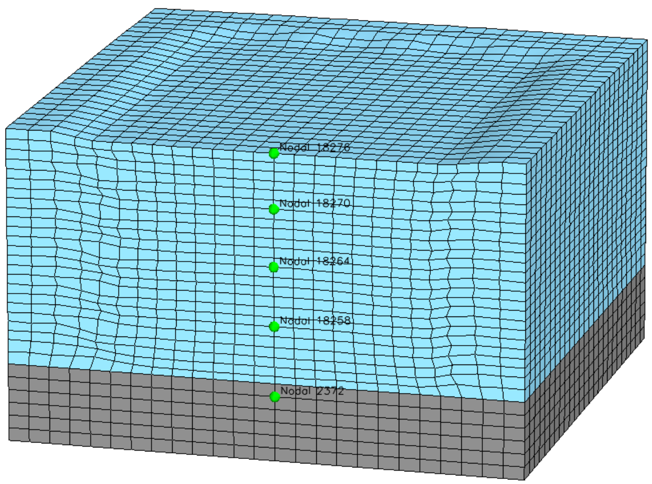
# Additional physics required to replicate single-track experiments

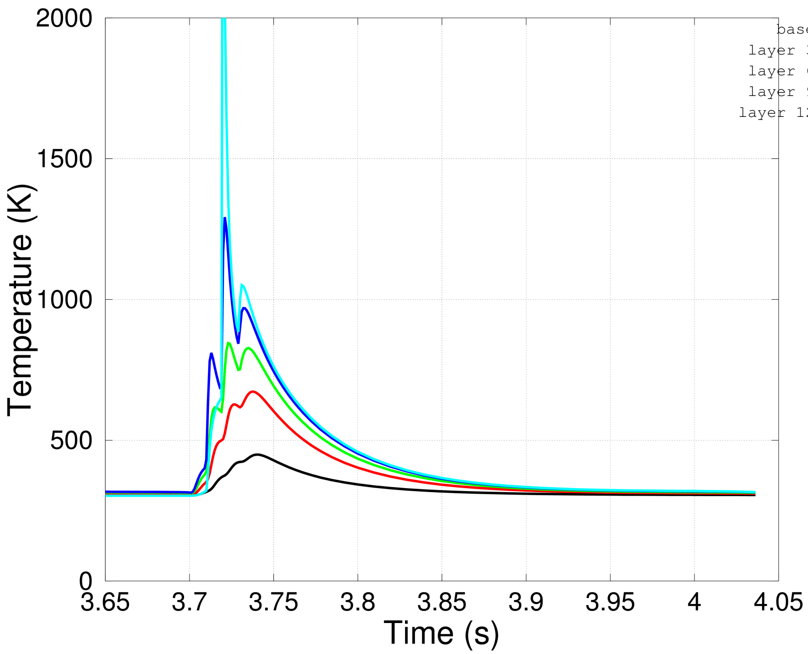
- Evaporation: analytical expression used to define a Neumann BC
- Recoil: phenomenological constitutive relation, implemented via anisotropic thermal conductivity




Knock-down factor not necessary if physics properly handled

# Layer-resolved simulations display the complex thermal evolution




- Cooling rates greater than $10^5$ K/sec

**Temperature histories can feed microstructure predictions**

# Overhangs: a common SLM challenge

- Lateral perforations require fusing above unprocessed powder to form downward-facing surfaces
- Impacts dimensional fidelity
- Impacts surface finish
- Do not want to re-machine internal passages

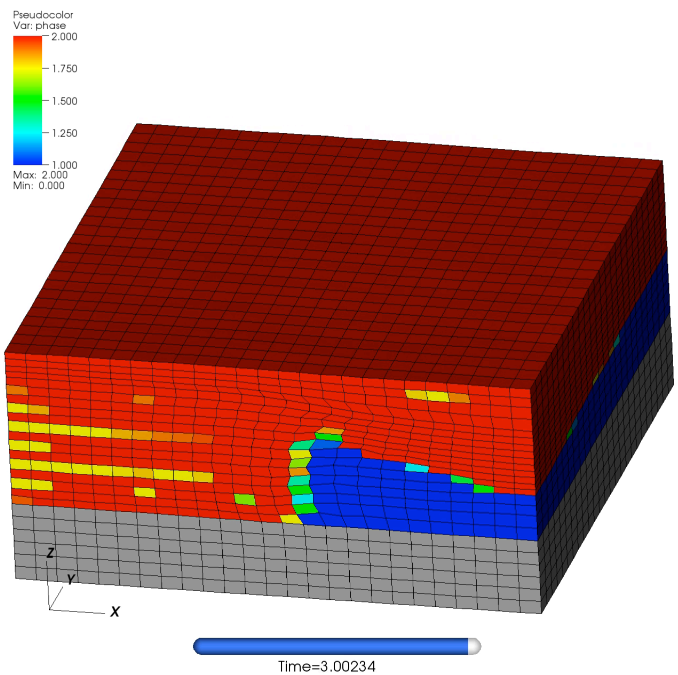
Cross section from horizontal tube*

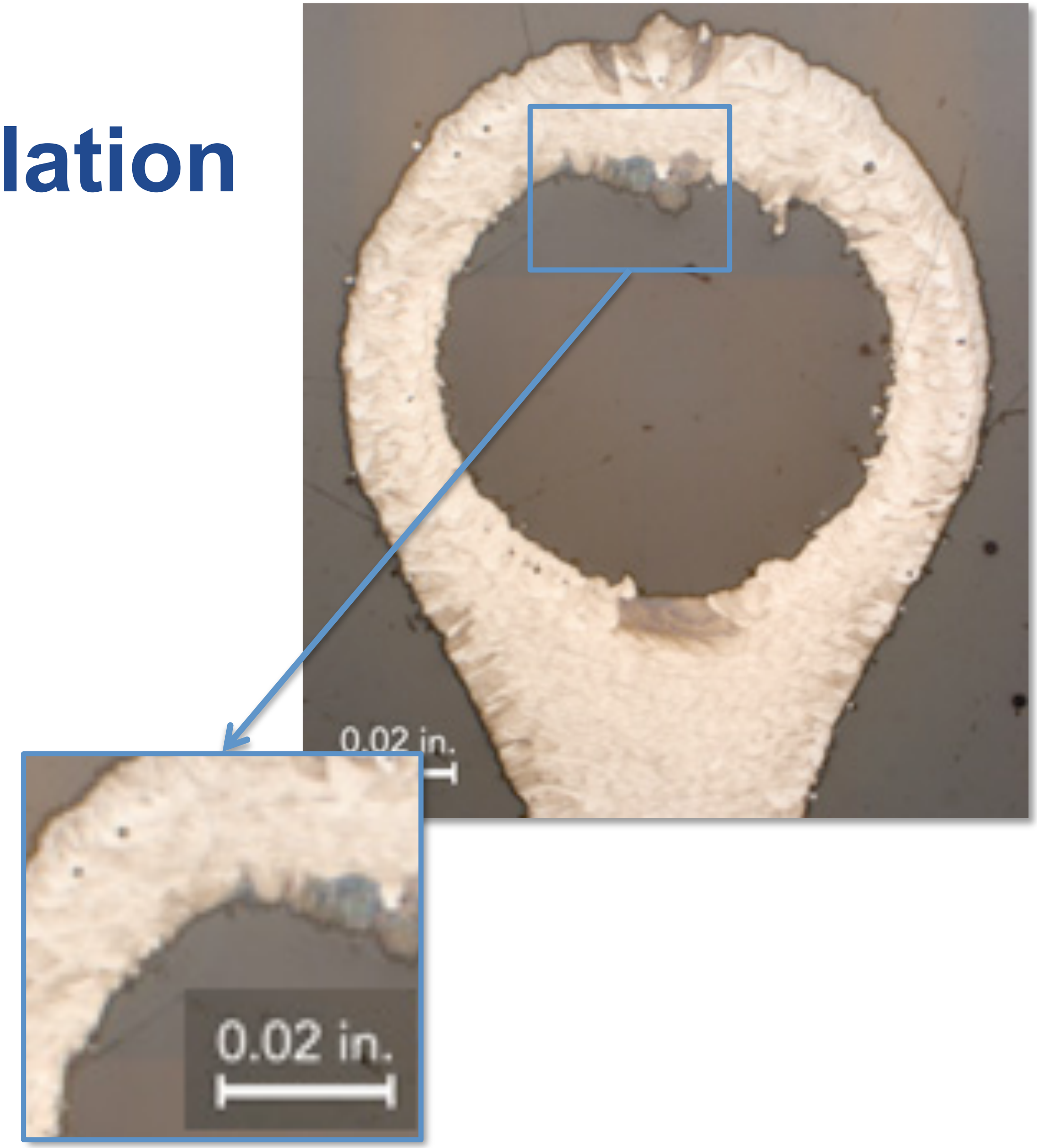

*http://www.industrial-lasers.com/articles/print/volume-28/issue-6/features/additive-manufacturing-at-ge-aviation.html

What can modeling show?

# Overhang simulation

- 0.5-mm overhang
- Constant laser power

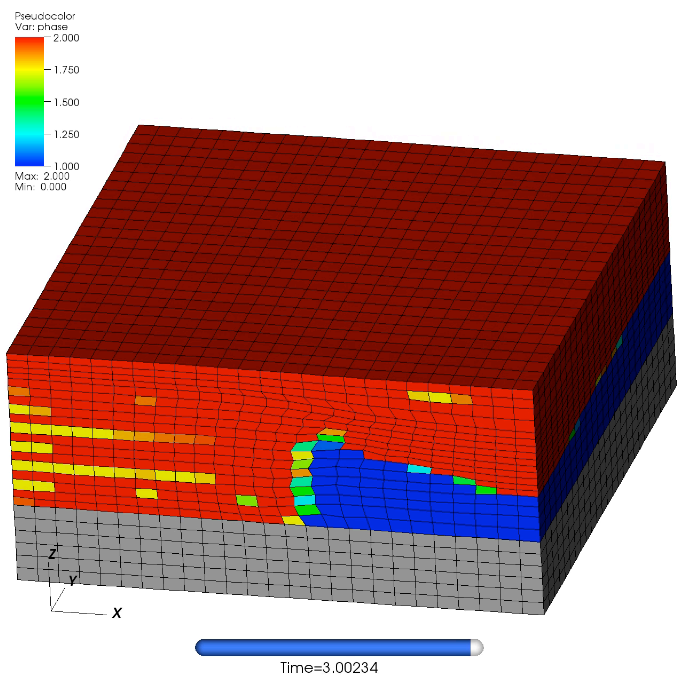


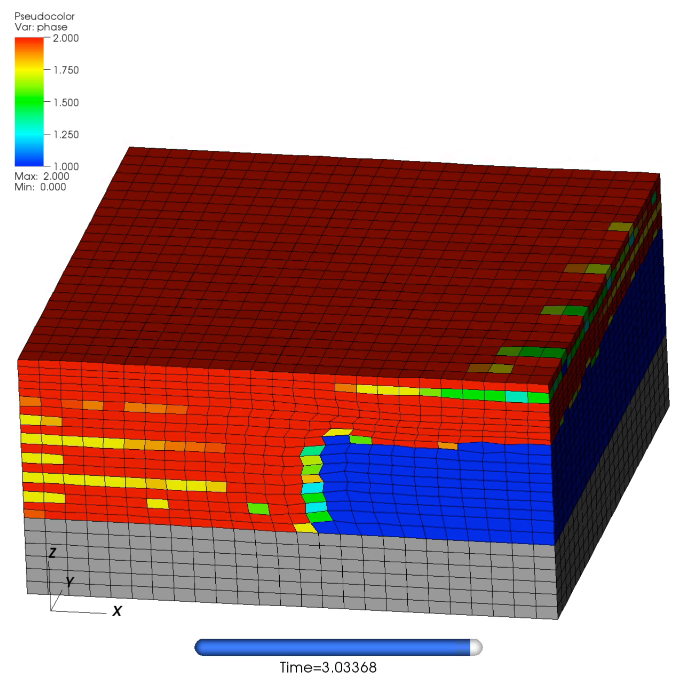

The impact of “thermal isolation” is clear

# Overhang mitigation simulation

- Constant laser power



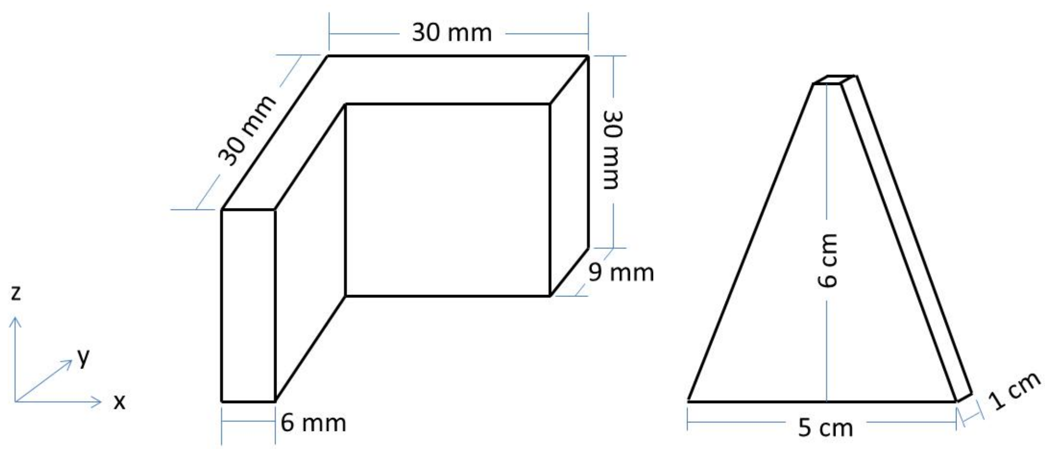

- Modulated laser power

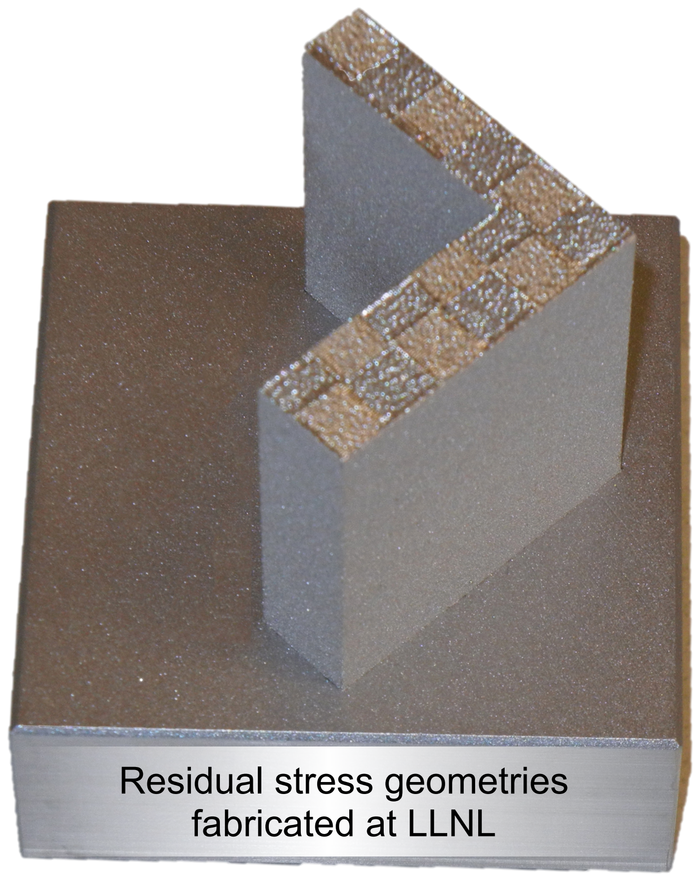



**Modeling and simulation can help identify mitigation strategies**

# Part-scale modeling creates added challenges

- From $mm^3$ to at least $cm^3$
- Time scale of global heat transfer
- Exploring further modeling abstractions
  - Aggregated layers
  - Aggregated scan



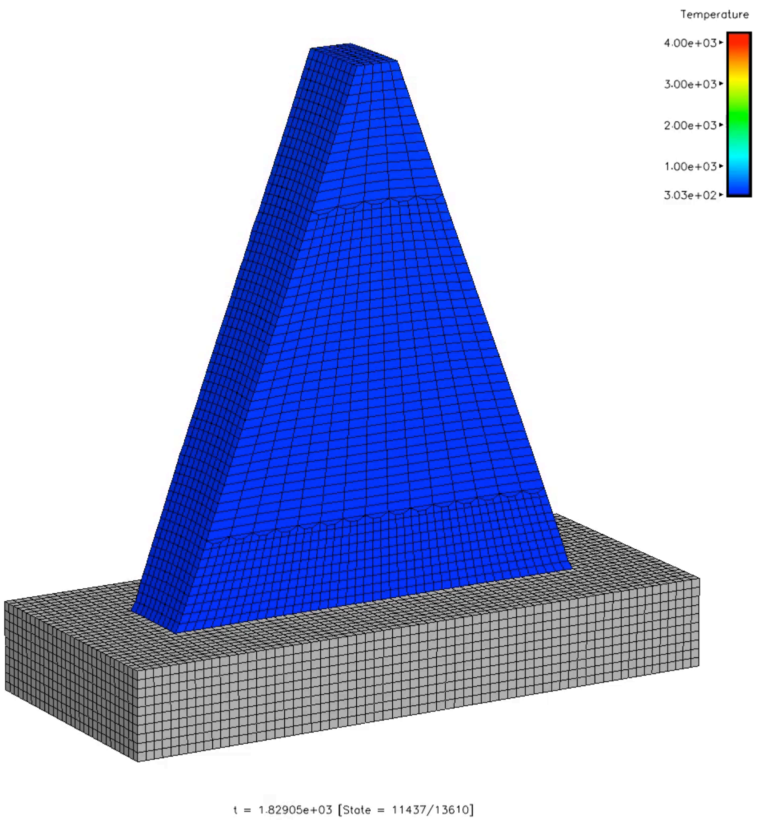



Residual stress geometries fabricated at LLNL

We have identified a baseline modeling strategy

# Part-scale modeling: our first attempt

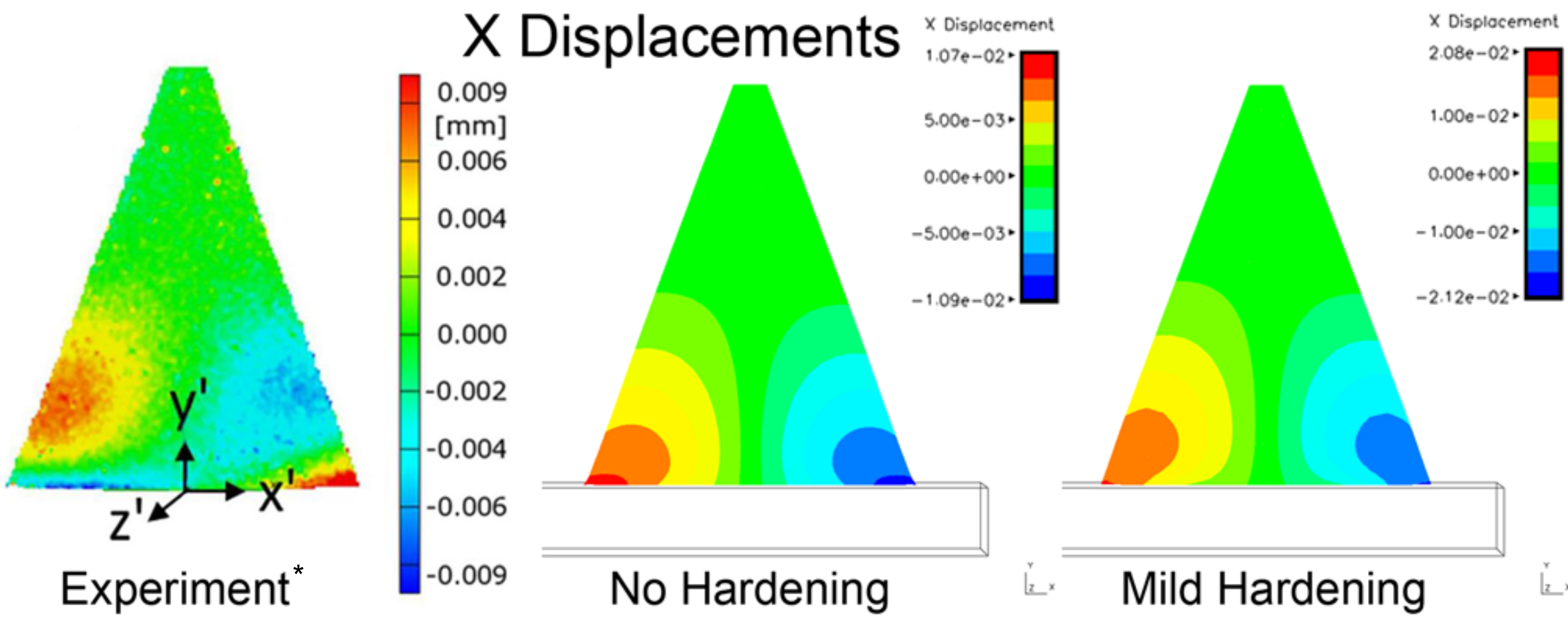
- Prism specimen: 316L, vertical build
- Original layers aggregated as 1-mm “super-layers”
- Coarse laser scanning
- Same plasticity model


Currently, we are ignoring powder outside the volume of the completed part

# We are validating the solids results

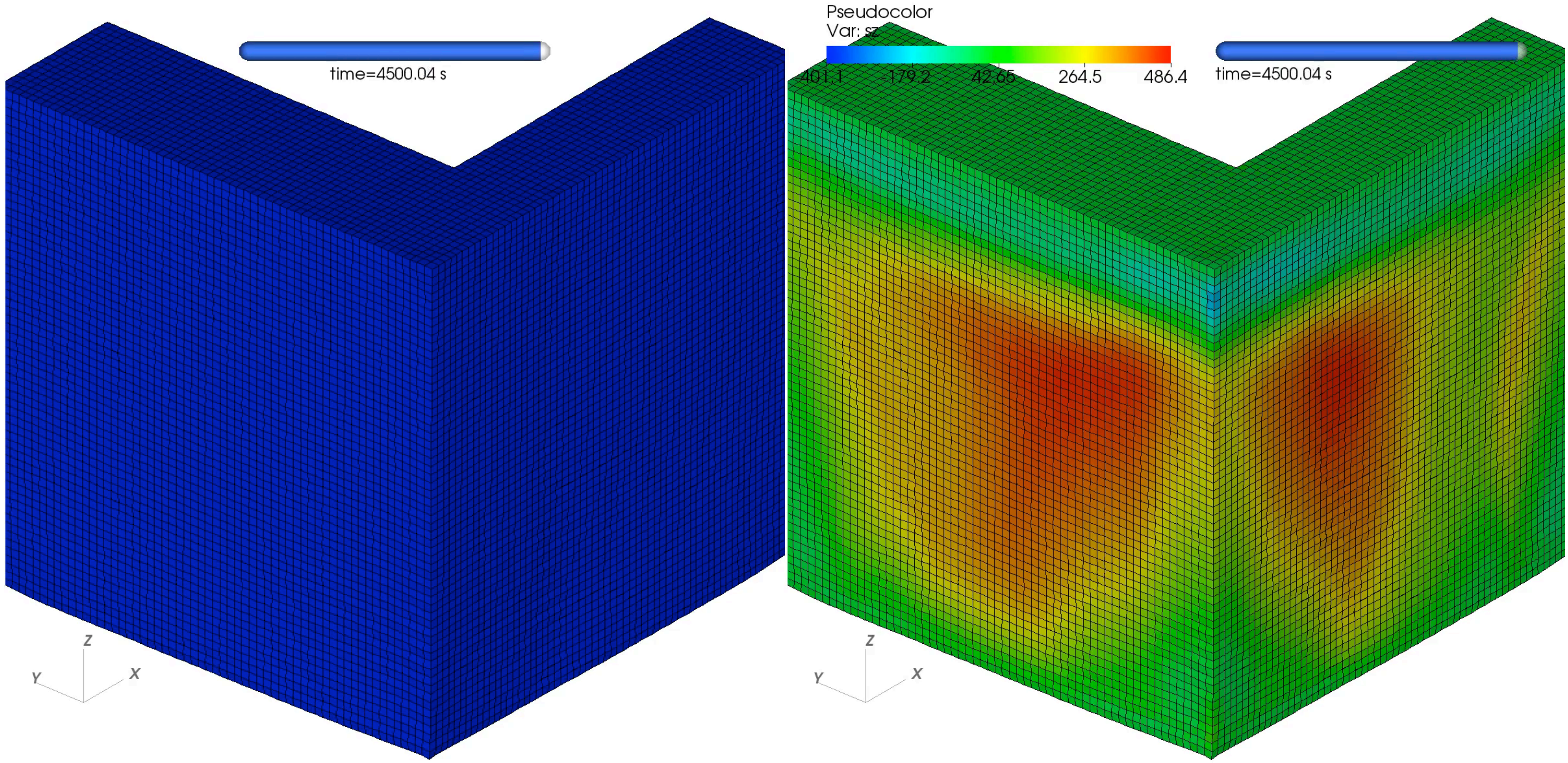
- Prism specimen (vertical build)
  - Incremental displacements due to build plate separation




*A. Wu, D. Brown, M. Kumar, G. Gallegos, W. King, "Additive Manufacturing Induced Residual Stresses: An Experimental Investigation," *TMS 143rd Annual Meeting & Exhibition*, February, 2014.

**Results are encouraging, while also showing sensitivities**

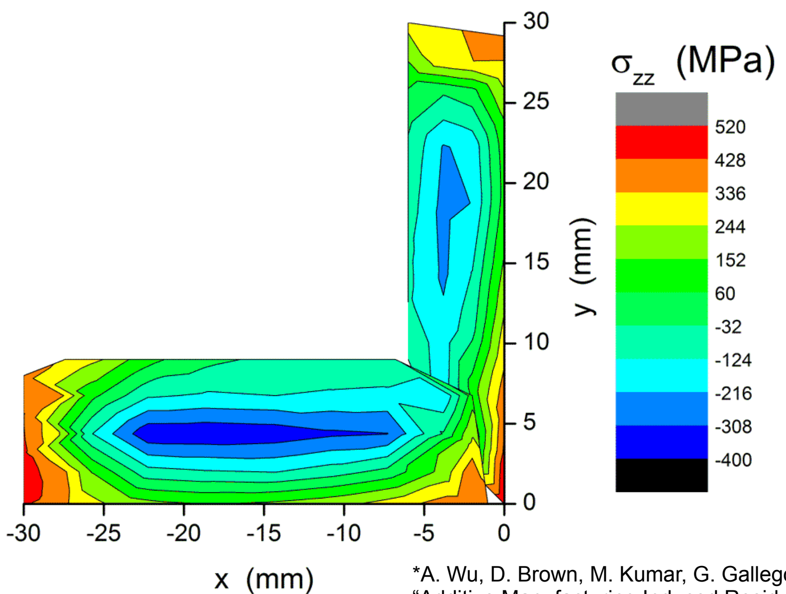
# Even for simple geometries, stress evolution is non-trivial




Baseplate removal causes significant relaxation

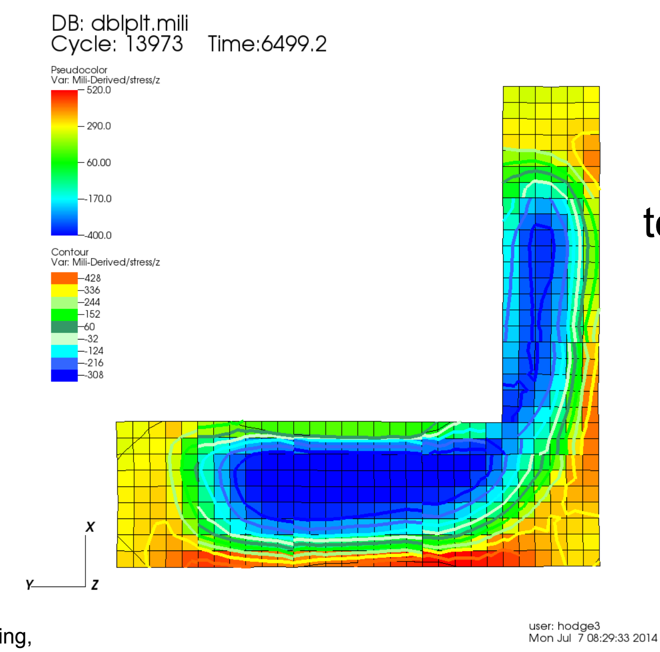
# Neutron diffraction data is another source of experimental comparison

- Vertical stress is assessed while on the build plate
  - Perimeter values are assessed from DIC for horizontal cut



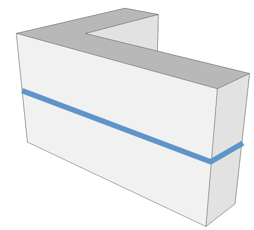

Experiments*

*A. Wu, D. Brown, M. Kumar, G. Gallegos, W. King, "Additive Manufacturing Induced Residual Stresses: An Experimental Investigation," *TMS 143rd Annual Meeting & Exhibition*, February, 2014.




Diablo

$\sigma_{zz}$ normal to plane 15 mm above base



These preliminary results are highly encouraging

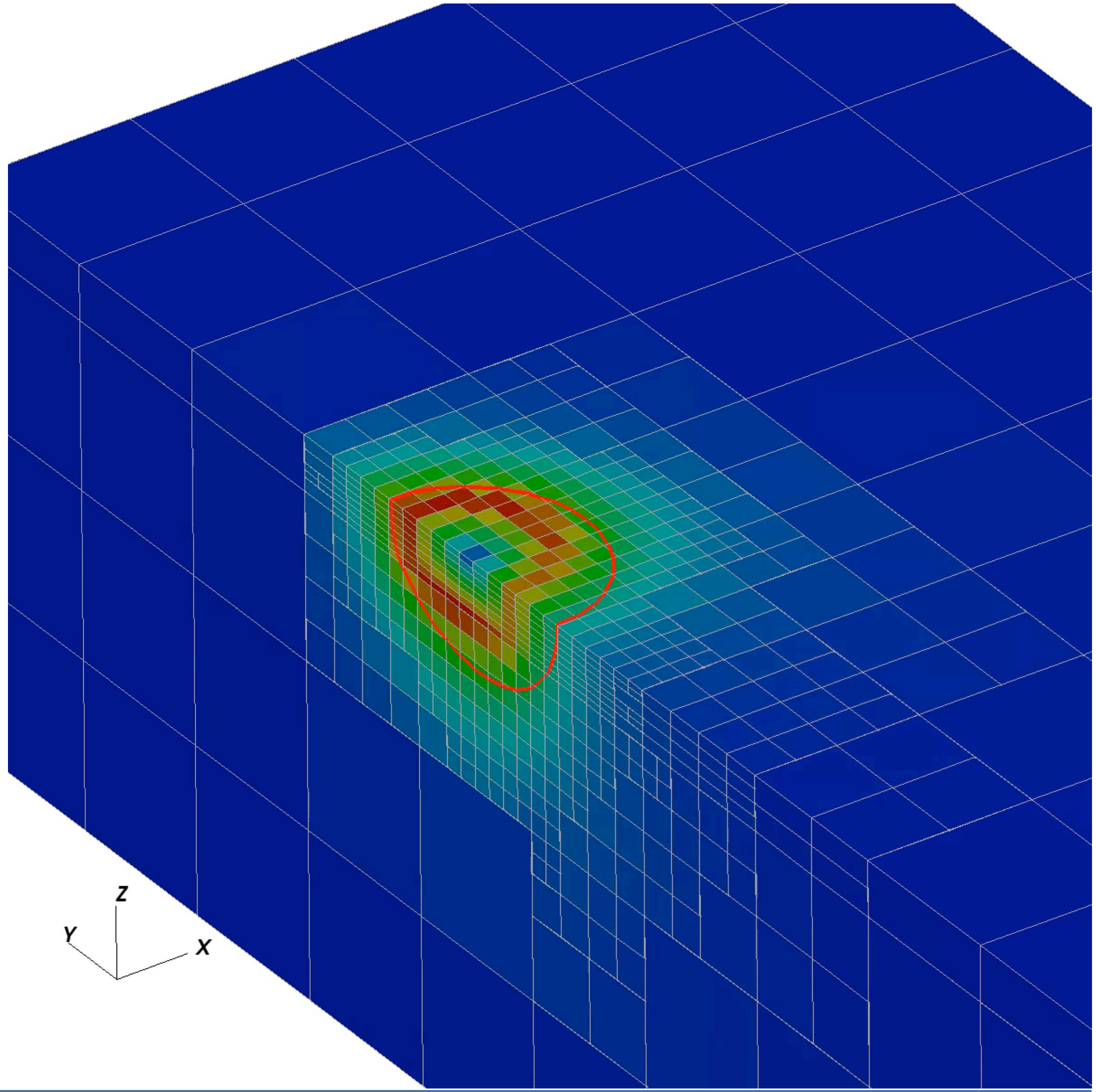
# Future work: physics and process

- Materials
  - General thermal-inelasticity (plasticity and creep together)
  - Determination and representation of multiple solid states
  - Integration with meso-scale models
- Fracture
- Laser path and power
  - Integration with machine control algorithms/software
- Support structures
  - Continuum, structural, both?
  - Integration with support structure generation packages
- Representation of build chamber/baseplate/machine influence

**Future requirements will require additional representations**

# Problems can take a long time to run

- It is not uncommon for $cm^3$ models to take on the order of hundreds of hours
  - Nonlinear physics, significant ratio of length scales
- Use AMR to decouple the different length scales
  - Initial testing indicates decreases in runtime in the range 50-100x versus the analogous (globally refined) mesh




Improvements in (throughput-accuracy) are "on the horizon"

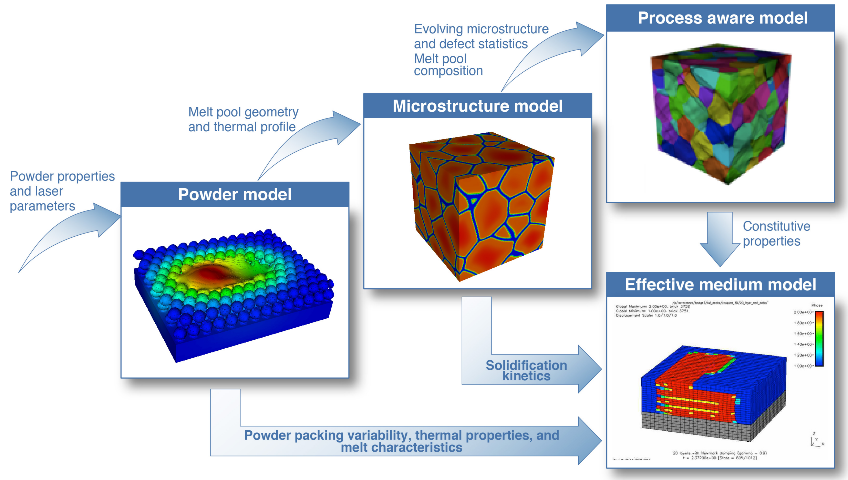
# Future work: Speed-accuracy

- Physics-dependent time integration (*i.e.*, time stepping)
- Physics- and/or spatially-dependent dynamics
- Improvement of phase change algorithm (consolidation and/or traditional)
- Discretization methods to handle geometry and multiple scales
  - Contact (*e.g.*, between part and baseplate)
  - AMR . . .
  - Higher order elements: polynomials, splines (solve two problems?)
- Integration with geometry definition
  - primary solid model generation
  - slicing packages

Work remains to get the desired performance and workflow

# Final Comments

- Extending a general purpose thermo-mechanical FEM code to part-scale modeling of the SLM process
- Modeling and computational strategies to date are promising
  - Distortions and stresses
- Need improved material representations, while simultaneously increasing speed
- Formalize data flows within our code federation
- Partner for user workflow utilities, from design geometry to SLM machine instructions



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