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Developing Digital Twins of Additively Manufactured Components

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G. C. Egan, W. P. Bassett, H. K. Springer, R. V.
Reeves, S. E. Watts, B. Giera, K. T. Sullivan, J. L. Belof

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EuroPyro 2023
Saint Malo, France
September 11, 2023 through September 14, 2023

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Developing Digital Twins of Additively Manufactured Components

Dylan J. Kline, Michael D. Grapes, Michael P. Hennessey, Samuel P. Mish, Garth C. Egan, William P. Bassett, H. Keo Springer, Robert V. Reeves, Seth E. Watts, Brian Giera, Kyle T. Sullivan, and Jonathan L. Belof

Energetic Materials Center - LLNL

EuroPyro

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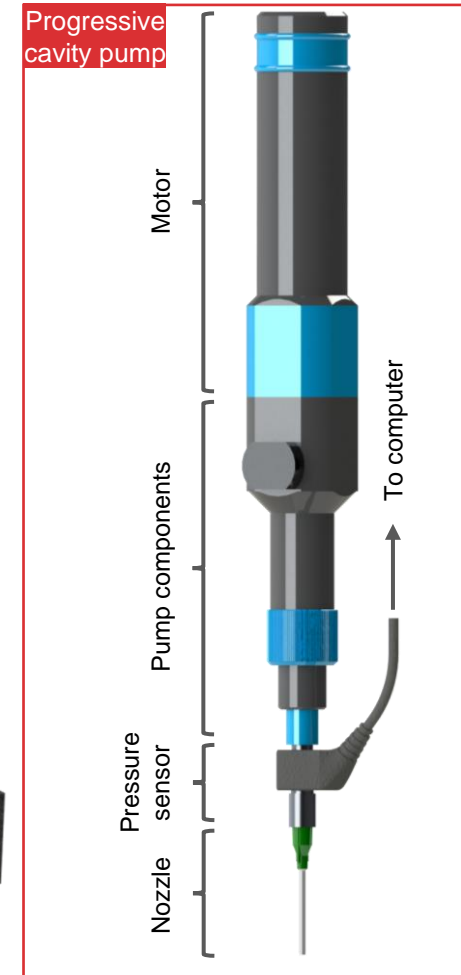
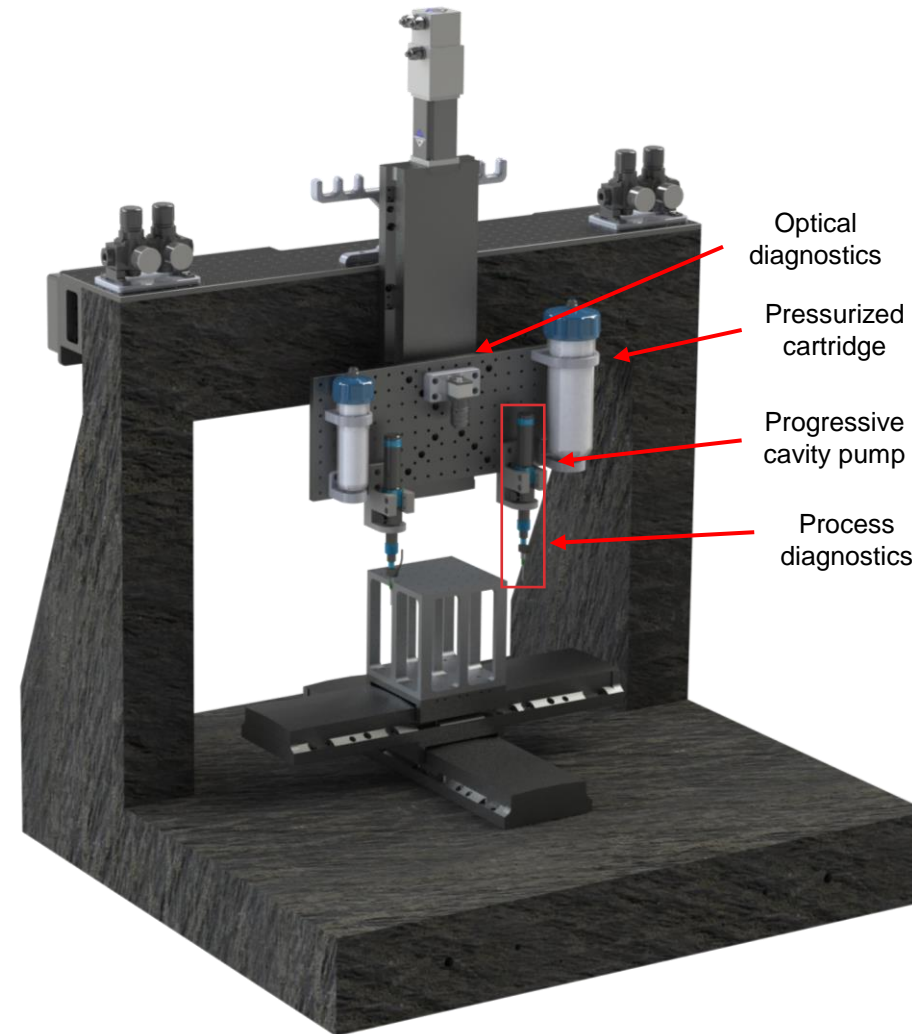
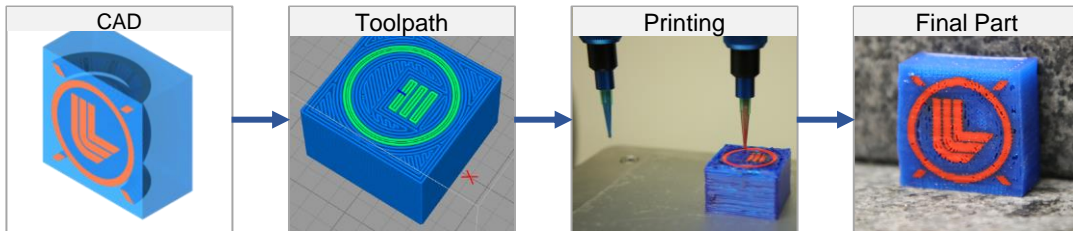


HE additive manufacturing at LLNL

LLNL is a leader in HE AM

- Progressive cavity pumps enable precise volume dispensing.
- Motion commands synchronized with material flow via custom software.
- Capable of multimaterial printing with discrete placement or gradient features.

Focused on creating high-density, volumetrically-accurate parts.

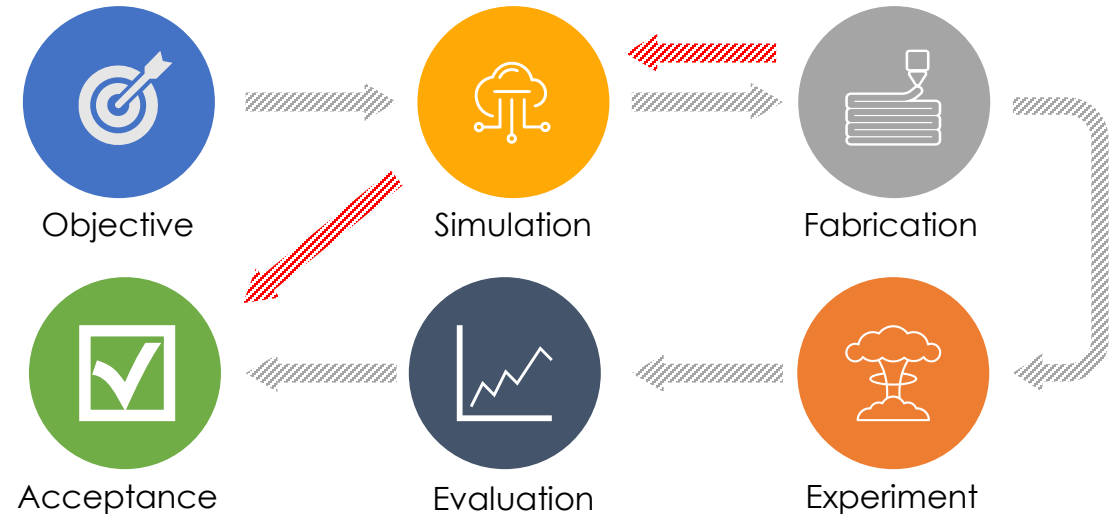


Digital twins and the experimental cycle

Goal: Develop digital twins to improve model accuracy and rapidly qualify parts.

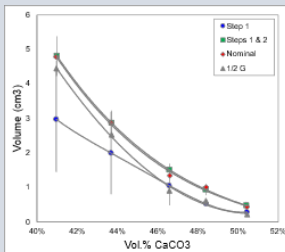
Focus: Reduce time in experimental cycle.

- Fabrication process introduces features.
- Feature-driven performance variations complicate simulation and qualification.
- Experimentation and qualification are the longest steps.



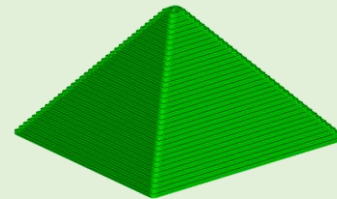
Material Formulation

Prepare materials with predictable behaviors.



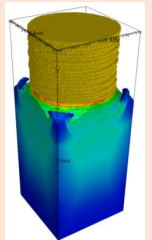
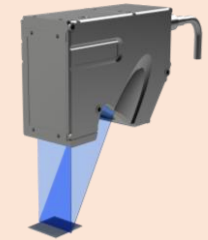
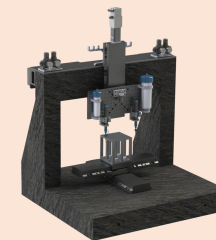
Toolpath Design

Predict performance with introduced features.



Printed Component

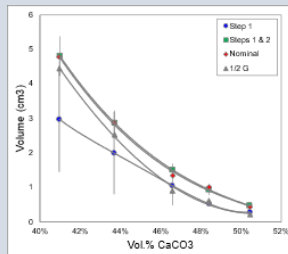
Develop in-situ diagnostics & simulate actual part.



HE AM digital twin thrust areas

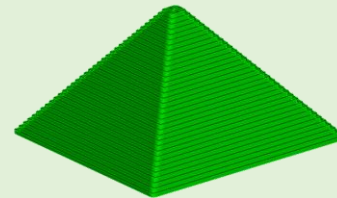
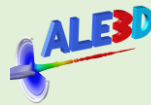
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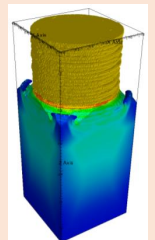
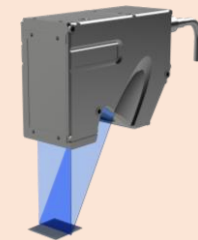
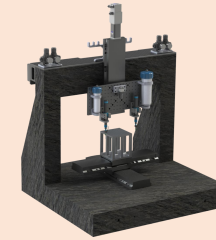
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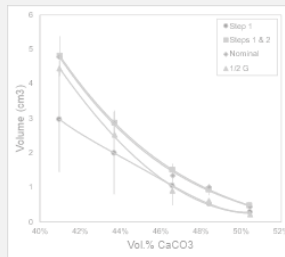
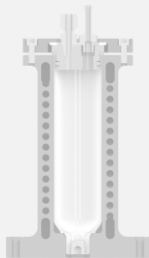
Develop **in-situ diagnostics** & simulate actual part.



HE AM digital twin thrust areas

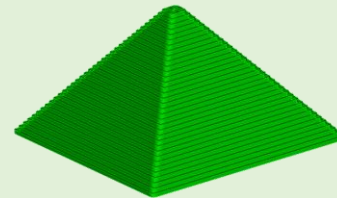
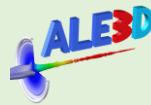
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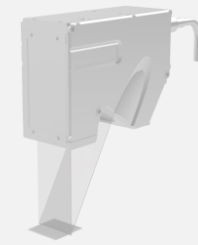
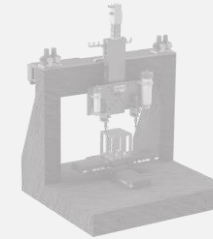
Toolpath Design

Predict performance with introduced features.



Printed Component

Develop in-situ diagnostics & simulate actual part.



Toolpaths, GCode, and slicers

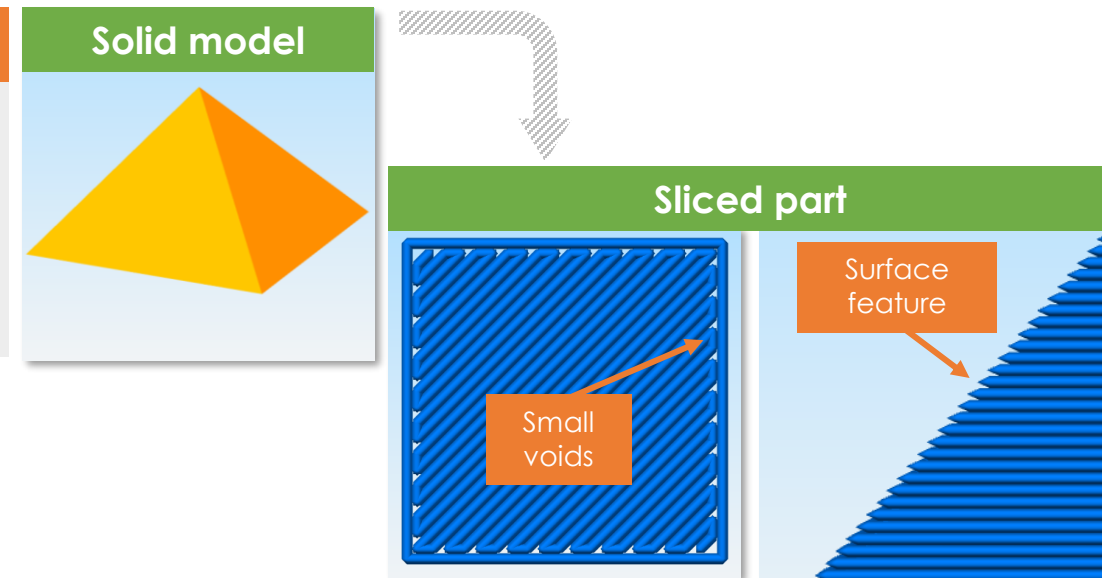
Before getting to the printer

- DIW **printers controlled using GCode** - instructions include tool number, coordinate position, movement speed, etc.
- **GCode generated using “slicers”** that take user-provided information to create thousands of lines of code.



Slicers and 3D printing artifacts

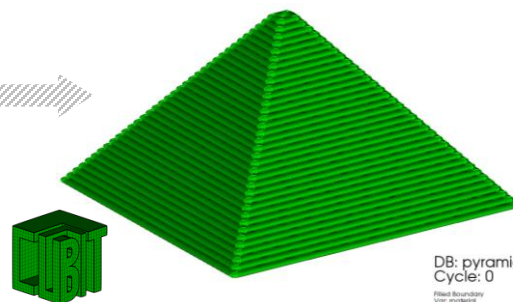
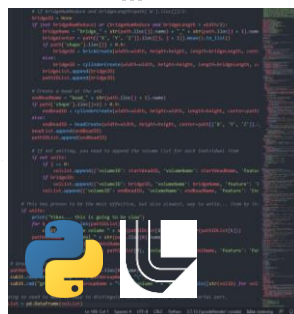
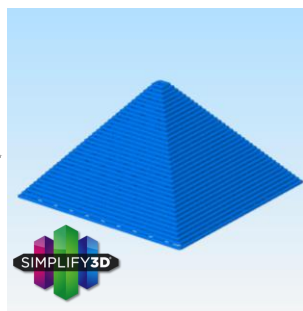
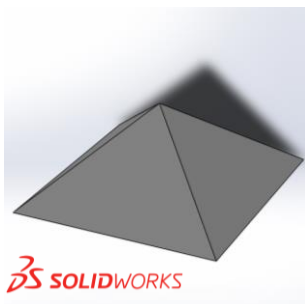
- Slicers are **not designed for volumetric accuracy**.
- Artifacts of 3D printing (e.g. voids in tight spaces) **may impact part performance**.



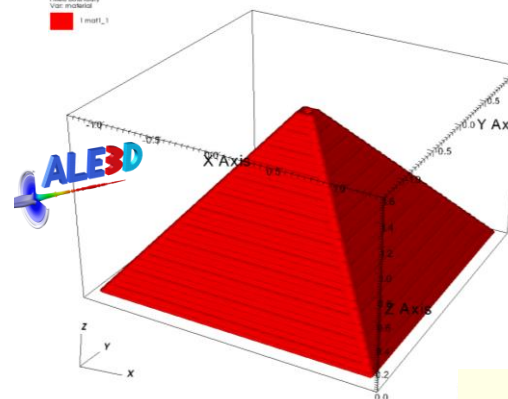
Rendered GCode

pyGCodeRender

- Python program converts Gcode to shapes for **direct import to hydrocode**.
- Render **multimaterial components**, subsectional rendering, variable filament morphologies, and more.

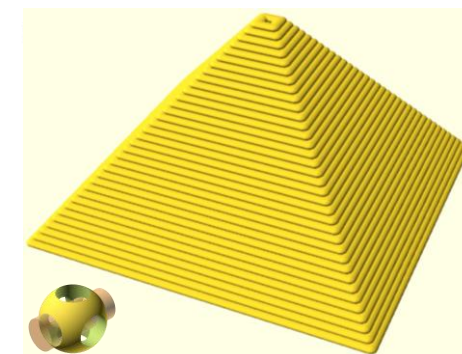


DB: pyramid_001.00000
Cycle: 0 Time:0
Open Boundary
Vor: incenter
1 mat_1



- Cubit / python interface for generating meshes used in marbl.

- Direct shaping in ALE3D using shape tool.



- Portable to other scriptable programs (e.g. openSCAD).

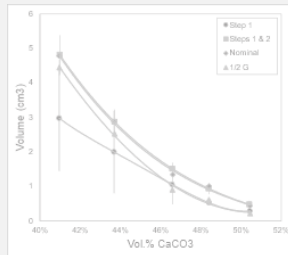
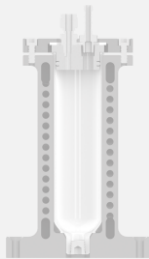
Future directions

- **Predict structural integrity** before fabrication.
- **Direct comparisons** between ideal part, prescribed toolpath, and actual part.

HE AM digital twin thrust areas

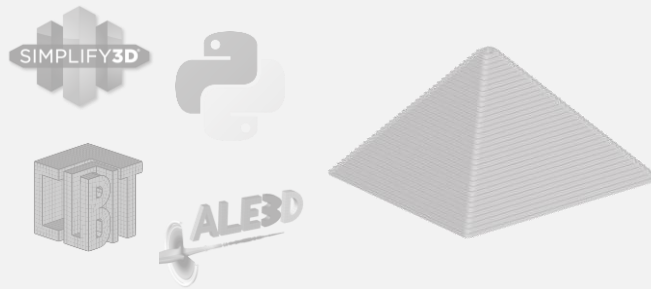
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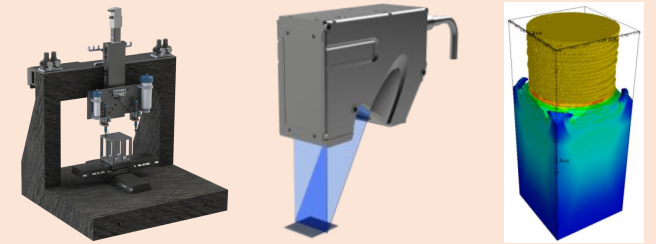
Toolpath Design

Predict performance with introduced features.



Printed Component

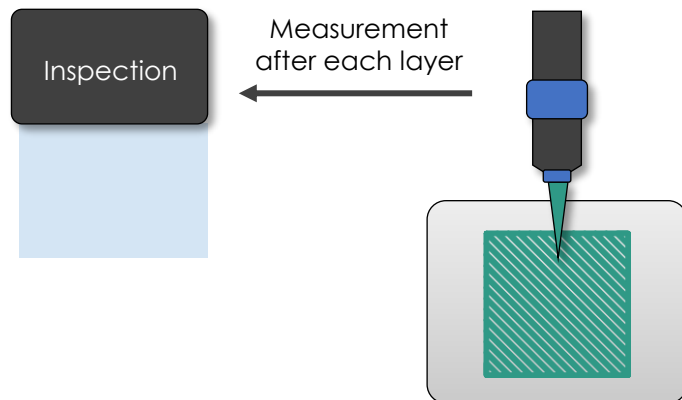
Develop **in-situ diagnostics** & simulate actual part.



In situ diagnostics options

Additive manufacturing offers native access for in situ diagnostics

- **Layer change routines** can be modified to include diagnostics measurements.
- In situ diagnostics have proven useful in **finding and fixing defects**.
- Data can be used to **create digital twins** of actual part.



	X-Ray CT	Camera	Spectrometer
Density	✓		
Color		✓	
Composition			✓
Time	Hours	< 1 s	< 10 ms
Resolution	~10 μm	~10 μm	~10 μm
Max area	cm x cm	>(cm x cm)	10 μm spot

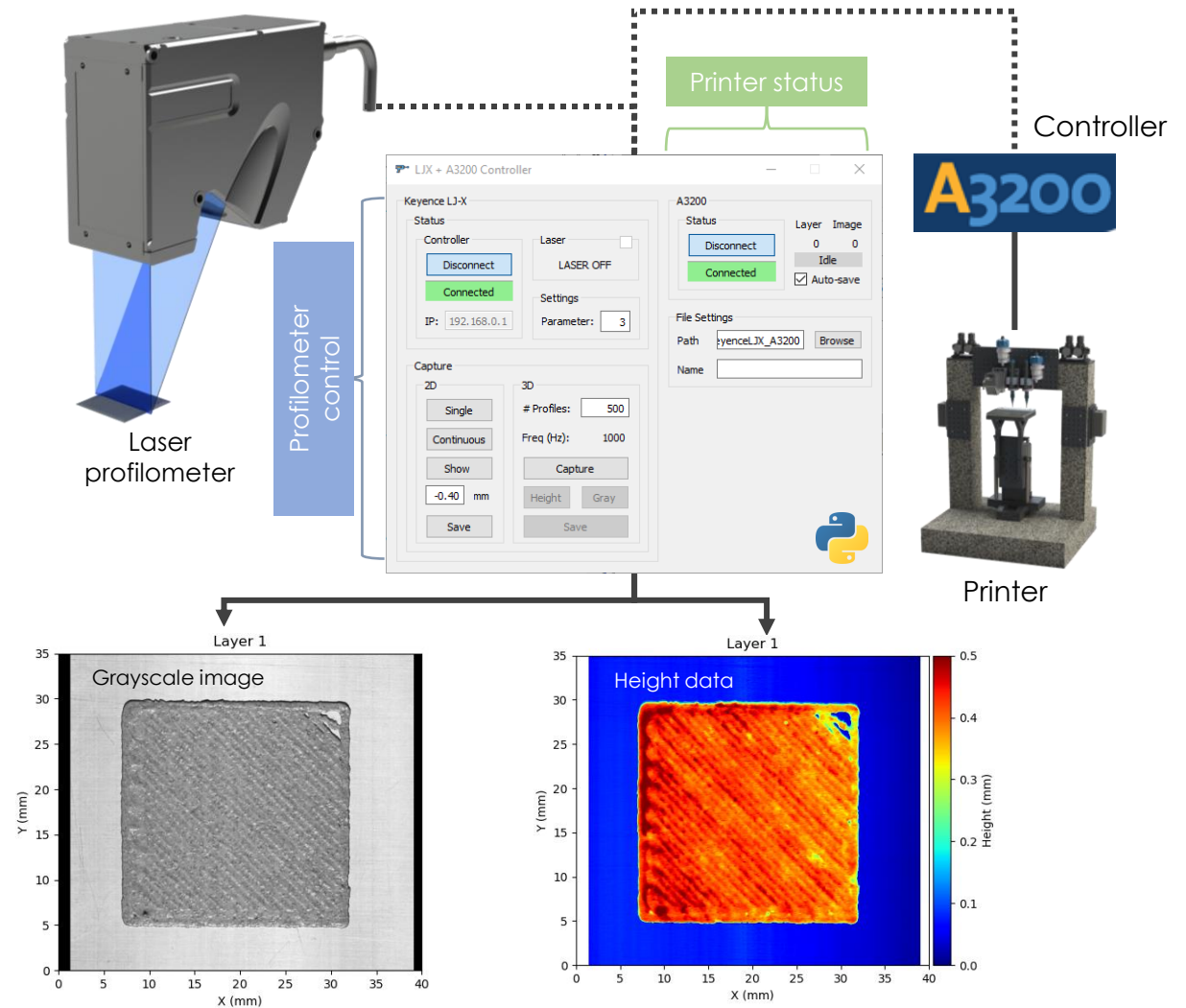
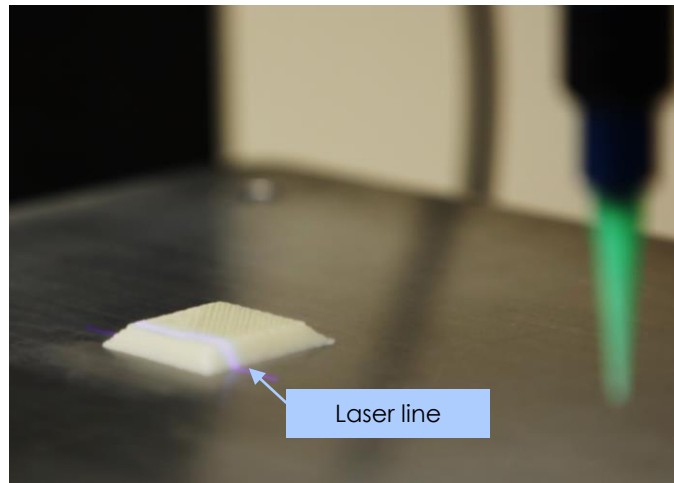
There may not be a “universal solution” ...

- CT: natively ex-situ, cannot distinguish materials with similar density.
- Camera: provides spatial color information only about exterior surface.
- Spectrometer: can identify composition, no spatial information.

Laser profilometry

3D measurements for advanced inspection

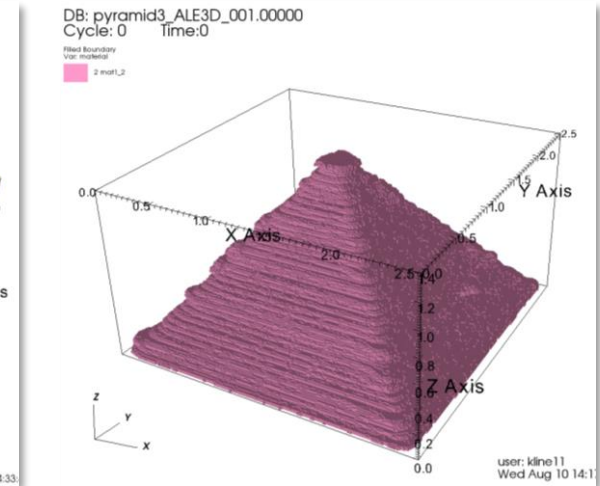
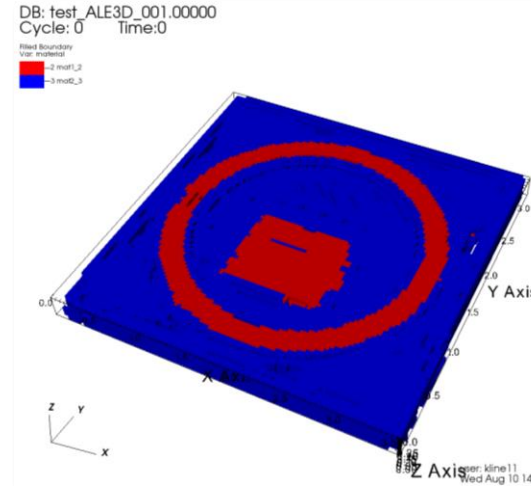
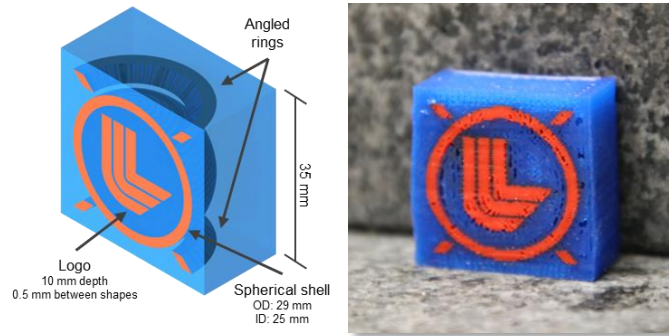
- Laser sheet projects onto surface and imaged using a CMOS sensor.
- Height information calculated using triangulation.
- **XY resolution: 12.5 μm , Z resolution: 1.6 μm .**
- Custom software enables laser **profilometer control using printer commands.**



Laser profilometry (continued)

Digital twins of test article

- Python processing pipeline **convolves height and grayscale information.**
- Able to **reconstruct a component** with embedded features.



Sliced part

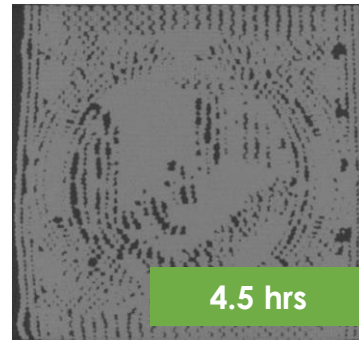
- Major features clearly identifiable.
- Minor defects.



10 minutes

Profilometer data

- Major features clearly identifiable.
- Local defects match actual part.



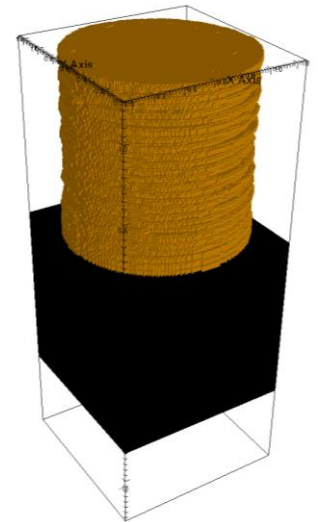
4.5 hrs

CT scan

- No identifiable features.
- Recovered filament morphology.

Direct simulation of digital twin

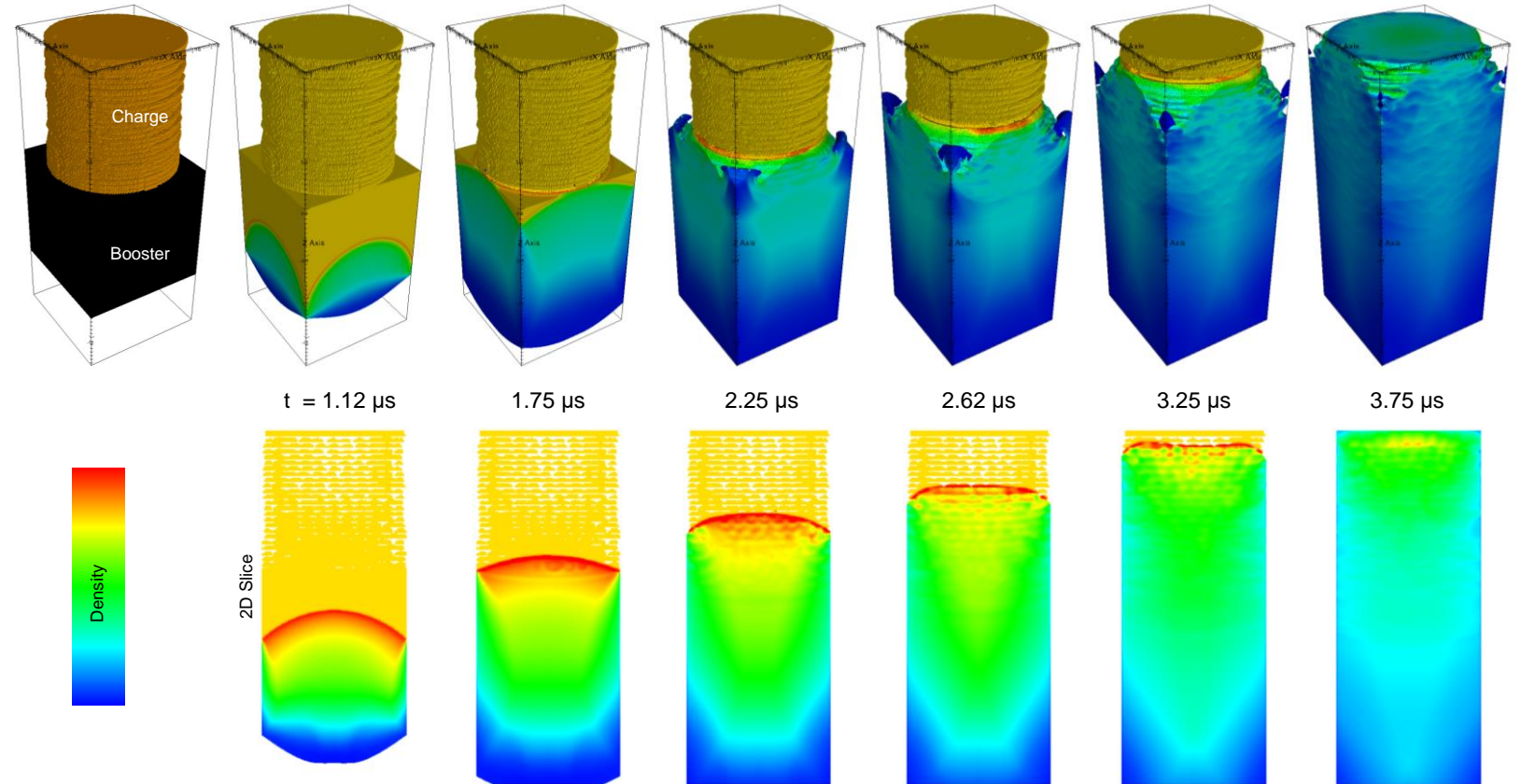
- Program written to **convert voxelized data** from profilometer directly into ALE3D.
- Capable of processing multimaterial objects for discrete placement.



Hydrodynamic simulations of reconstructed parts

Simulations of digital twins show effect of pores.

- Inert HE cylinder scanned in-situ and imported into ALE3D for simulation.
- Internal pore morphology arising from filament spacing impacts detonation front.
- Possible **future avenues for research** on tailoring shock fronts using filament morphology.



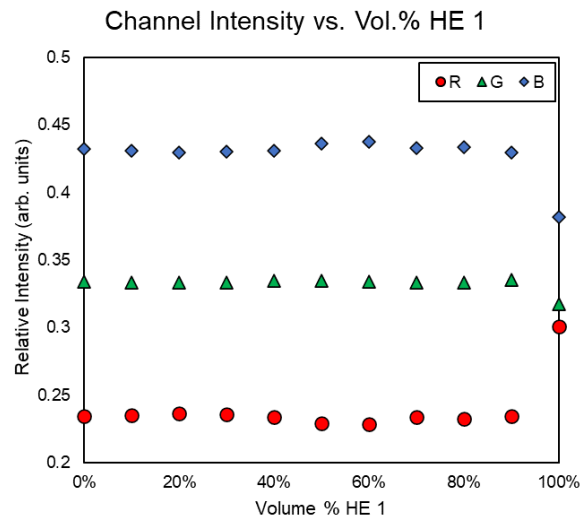
Raman spectroscopy for graded components

When your eyes fail you...

- Composition is **impossible to identify** for mixtures with very different particle sizes.

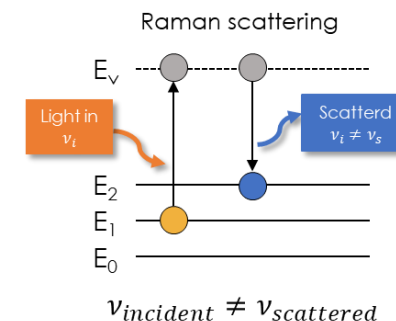


- Color-based **image segmentation not suitable** for mixtures of common materials used in HE AM.
- Hyperspectral imaging unable to identify differences in composition.

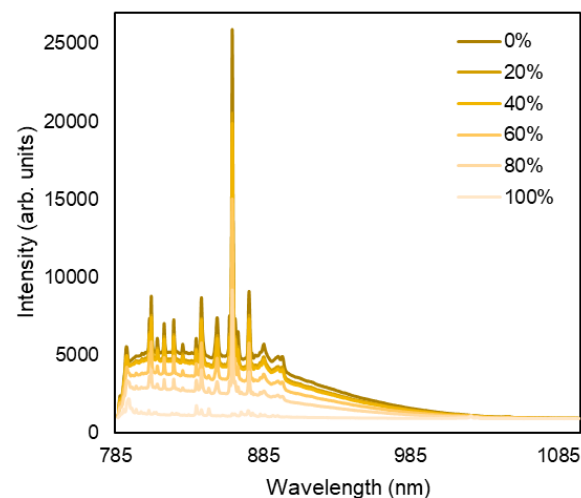


... use spectroscopy

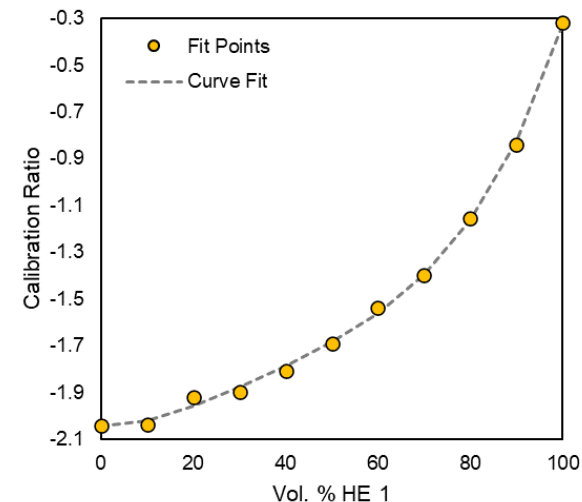
- Raman spectroscopy can be used to **identify chemicals** and can provide **quantitative compositional measurements**.
- Standardized samples measured with Raman spectroscopy and used for composition calibration.



Raman Spectra for Mixed HE



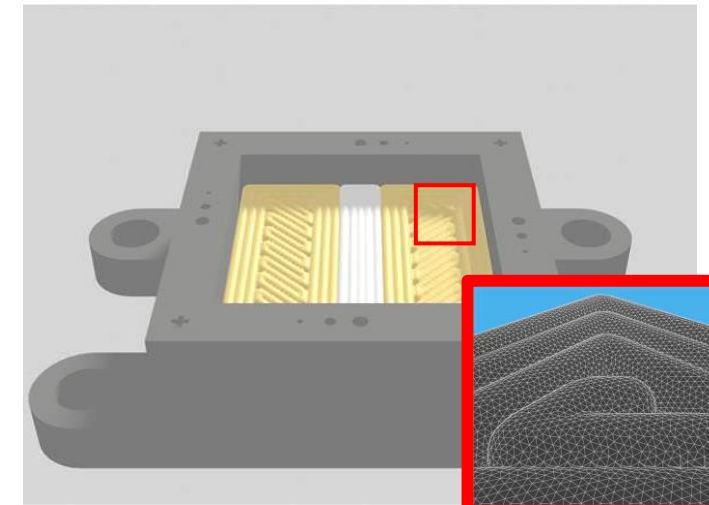
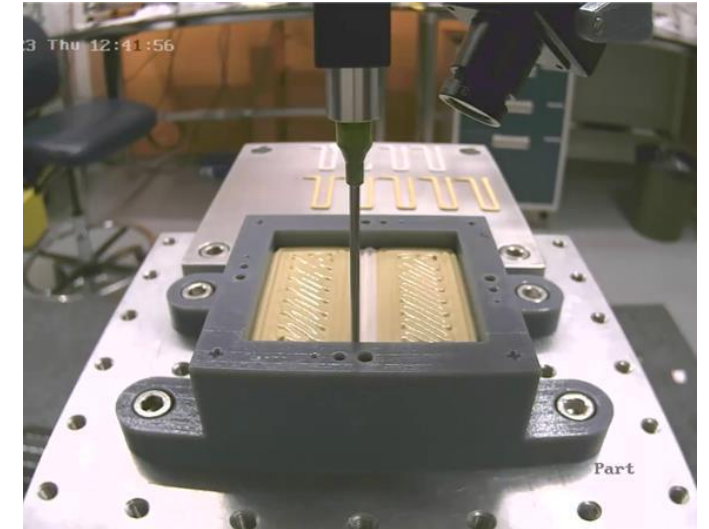
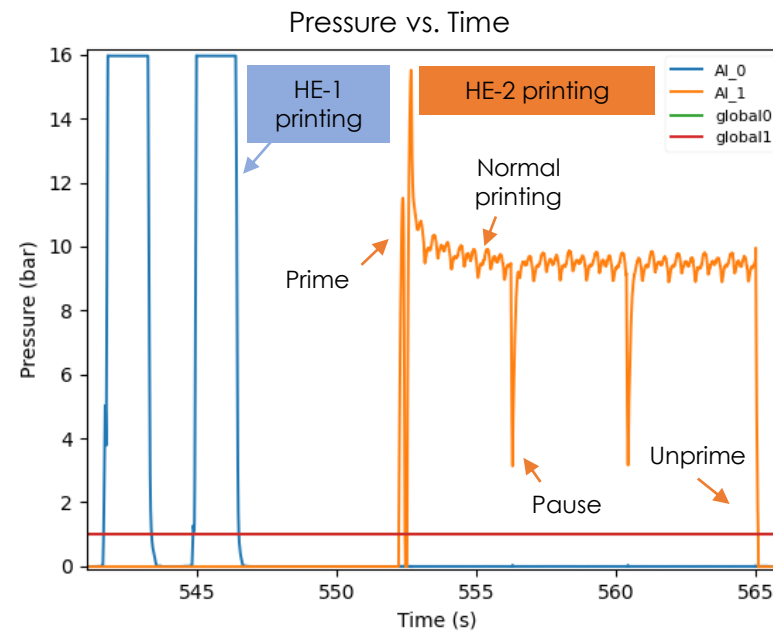
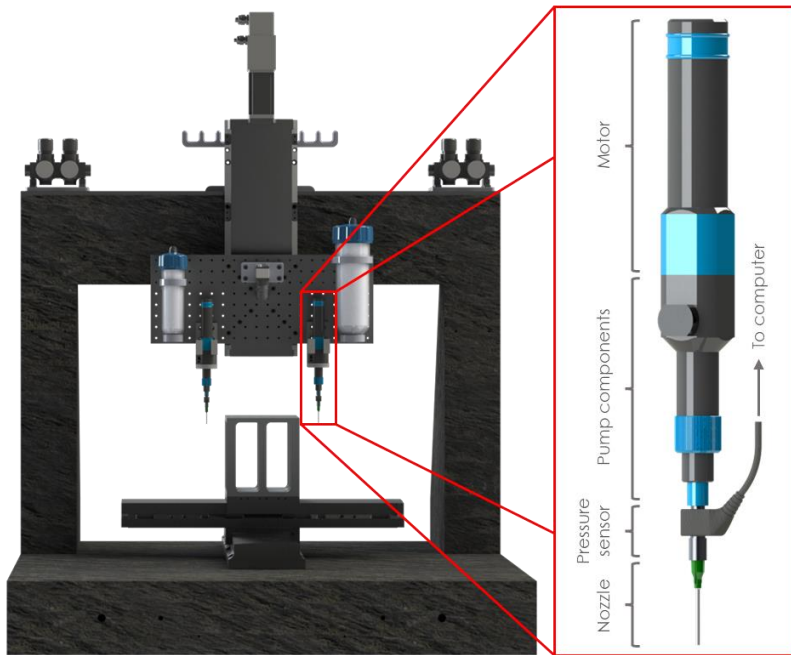
Calibration Fit for Mixed HE



In-situ process monitoring diagnostics

Digital twins from process data

- Pressure values at the nozzle can be correlated to material flowrates in the system.
- Data collected about pressure at the nozzle has been used to **reconstruct a multimaterial part using only machine data.**
- Meshes generated using a custom parallelized meshing software.



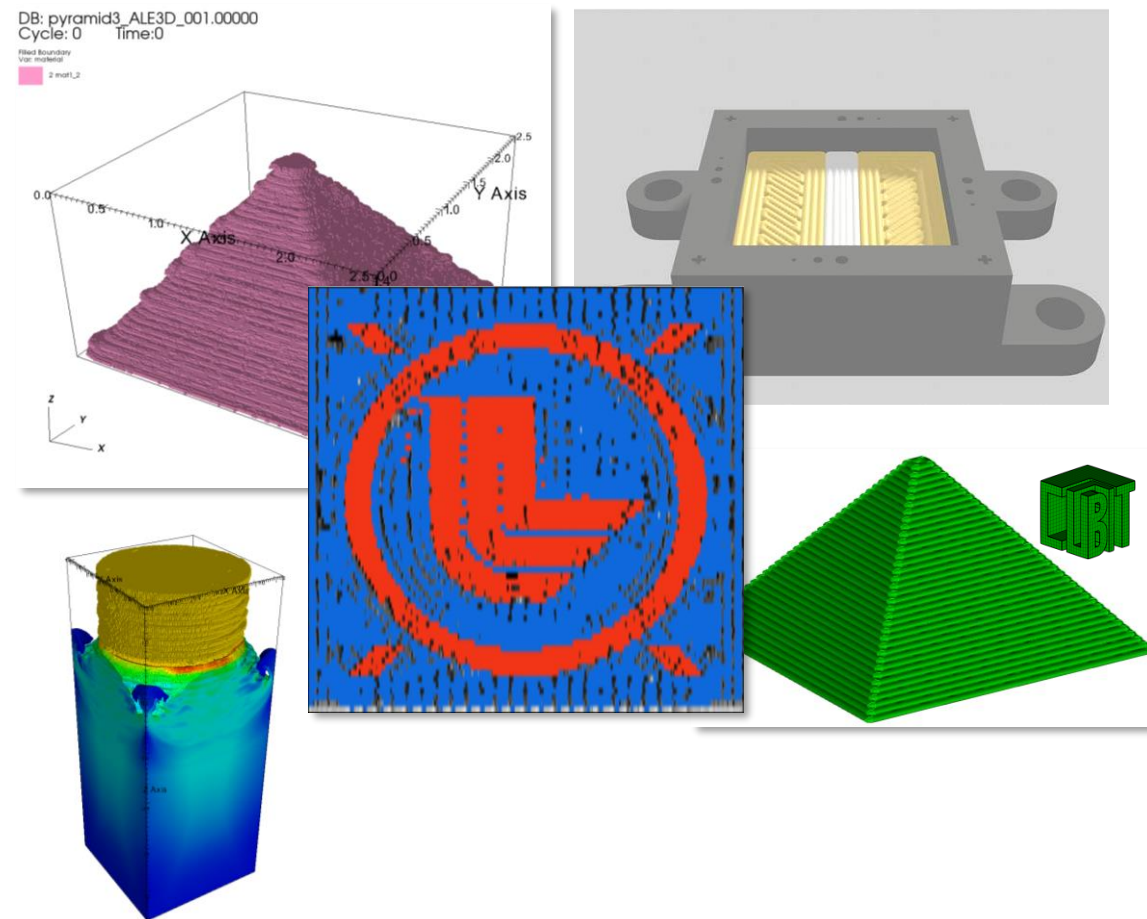
Summary

Multi-pronged approach to rapid qualification

- Demonstrated multiple ways to **predict and measure performance of HE AM components**.
- No “one-size-fits-all” solution to in-situ diagnostics – the tool needs to be chosen based on the context.
- Pathway for **rapid data analysis and import for direct simulations** may enable rapid qualification of components.

Future directions

- In-line measurements for graded compositions.
- Expanded library for compositional gradient mapping.
- Import of large meshes into next-gen hydrocodes (e.g. marbl).
- Improvements in diagnostic workflow for components printed into unique geometries (e.g. into a mold or nonplanar surface).





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Icon Library



Background Textures



Logos



Logos – reversed





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