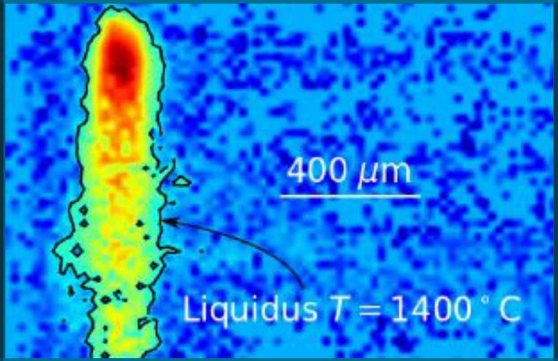
Sandia National Laboratories

SAND2019-13200C

Detecting Process Defects in Laser-Powder Bed Fusion



PRESENTED BY

Bradley Jared

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Outline

Motivation

Part design

Porosity reconstruction

Melt pool monitoring

Data correlations

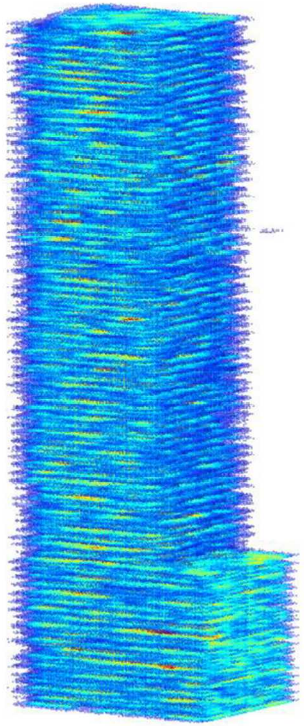
Summary

Material Assurance

Material formation concurrent w/geometry
- want to predict part/material performance
- qualification / acceptance requires
  - significant design margins
  - understanding defect impacts on performance

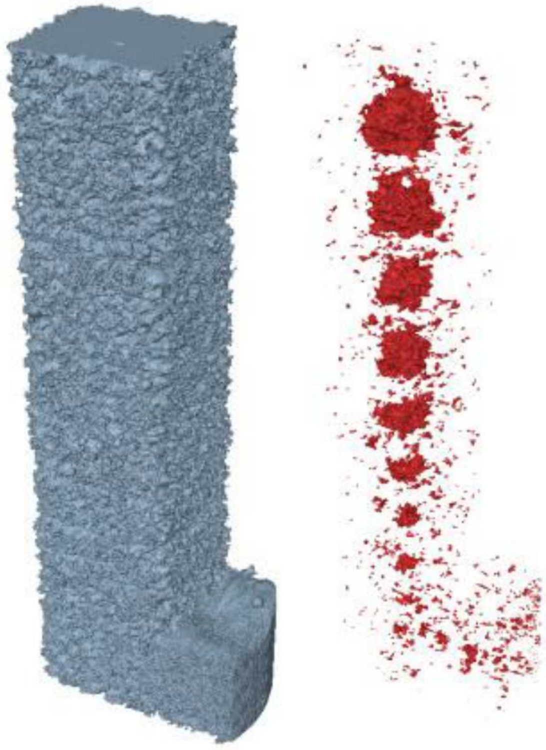
How to ID a bad part?
- proof testing
- non-destructive inspection
- *process monitoring*

Objective
- correlate spatial sensor data (X,Y,Z,time) to material porosity (X,Y,Z)



part pyrometry field

???

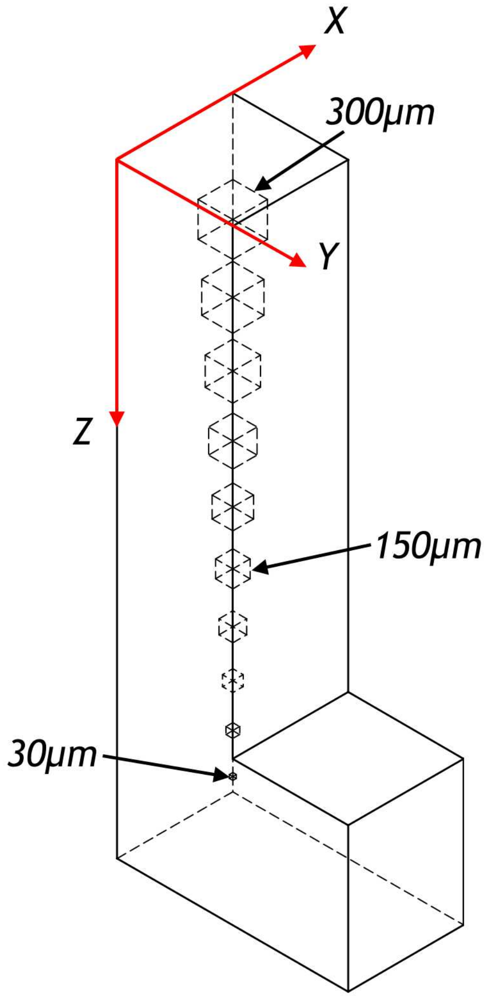


part porosity field

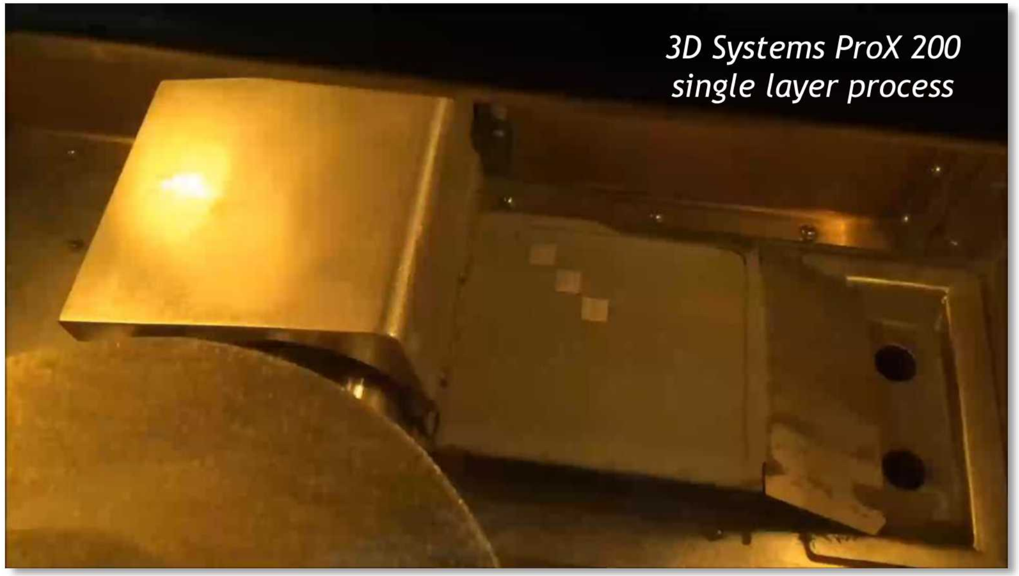
Captured Holes Structure

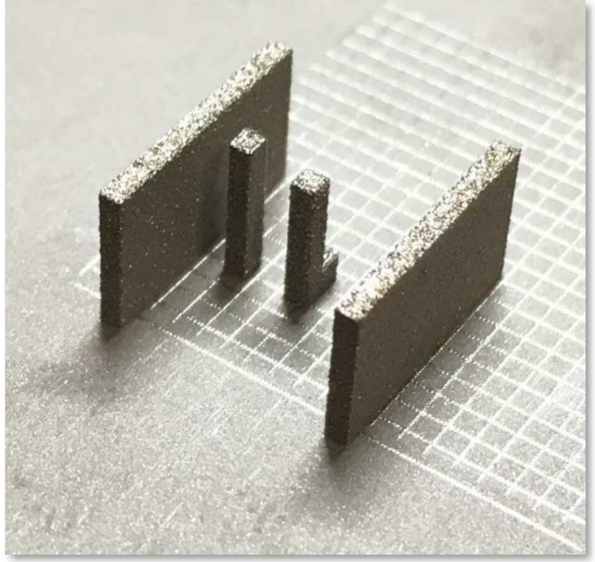
Design
- 1x1x5.25mm column, 175 layers
- holes
  - 1-10 layer thickness (30-300μm cubes)
- 316L stainless steel

Material characterization
- Zeiss Xradia 520 Versa μCT
- voxel resolution: ***1.98μm***



captured holes design





captured holes part printed in 316LSS

Material Reconstruction

part side view

micro-computed tomography

Adobe Photoshop

batch processing
16bit > 8bit conversion
lossless filetype conversion

FIJI

alignment &
registration
cropping
grayscale matching
autoleveling
image filtering
thresholding

MATLAB

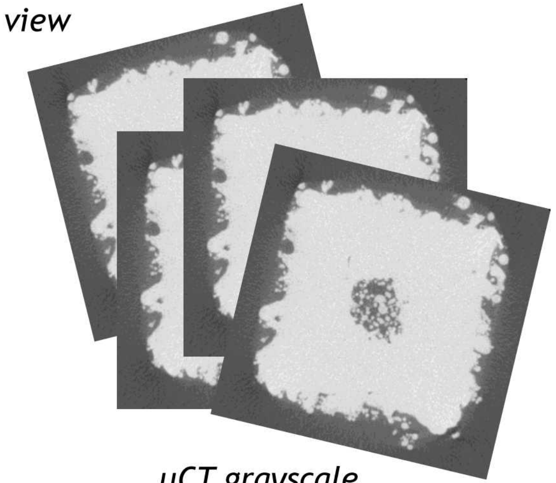
Interactive Data Language

IDL

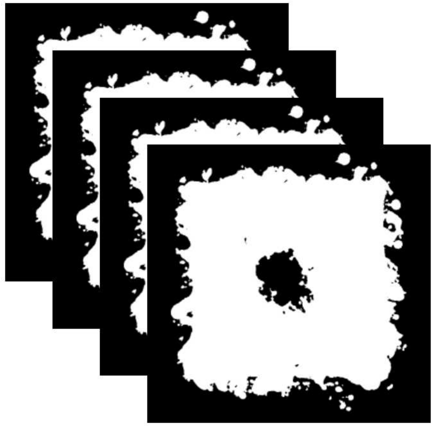
reconstruction
quantification

ParaView
Parallel Visualization Application

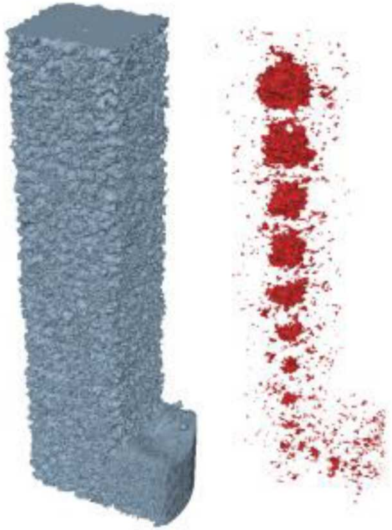
image processing
visualization



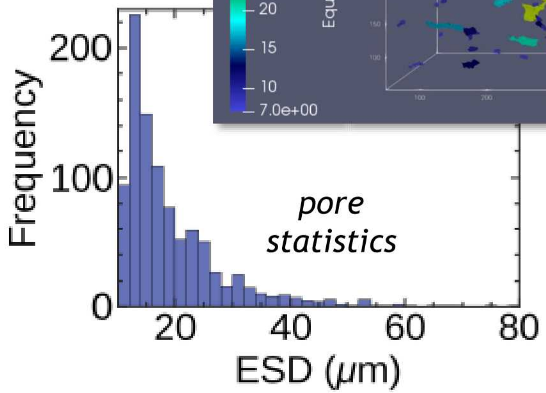
µCT grayscale image stack



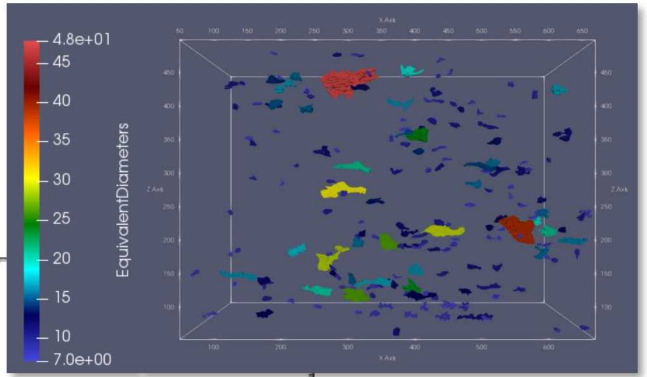
aligned & segmented bitmap stack
white = material, black = air/void



part reconstruction



pore statistics



porosity map generated near the 10 & 20µm pores

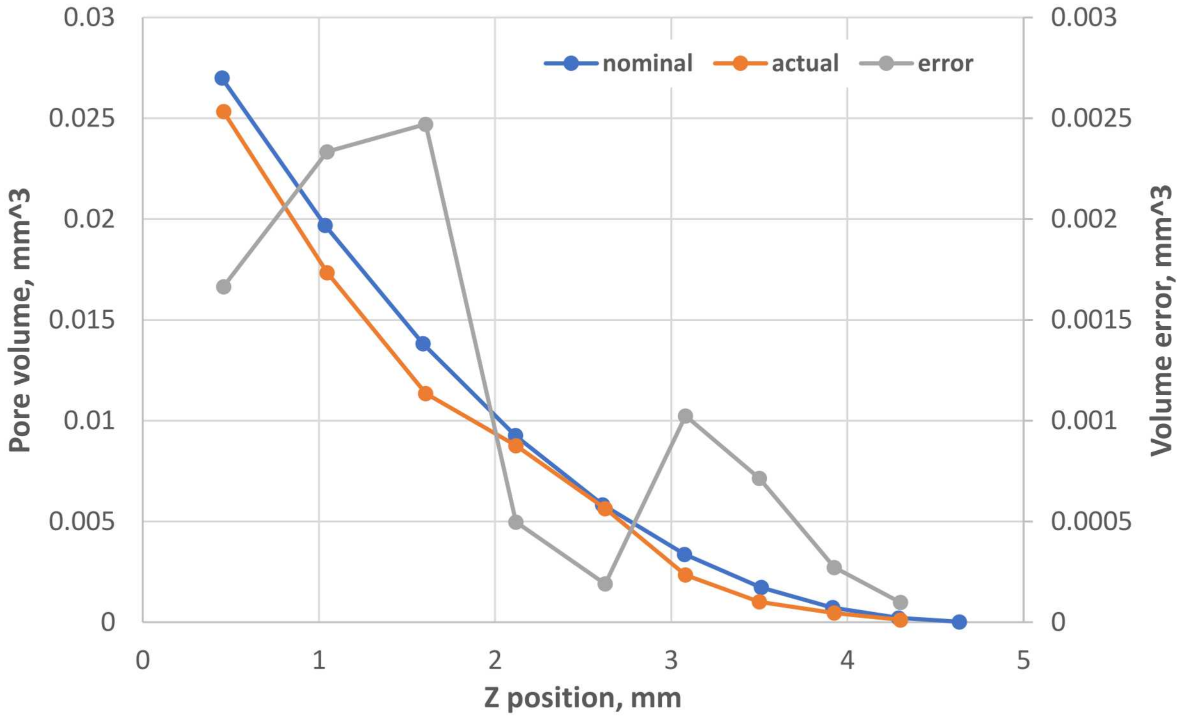
Identifying Captured Holes with µCT

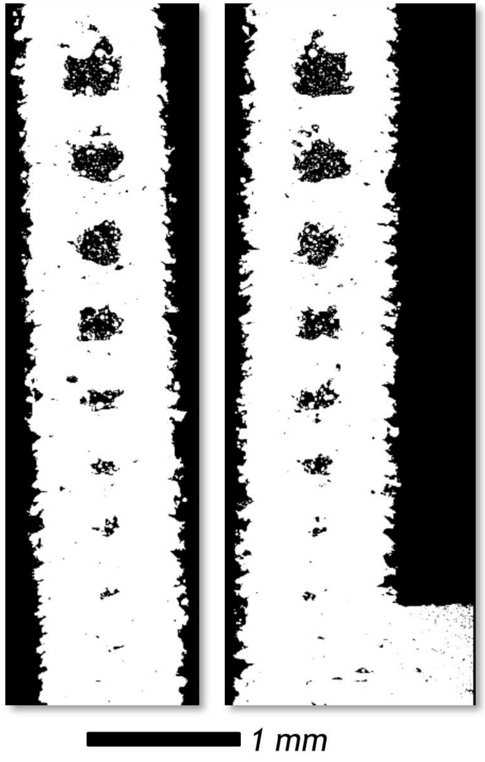
Features are extremely coarse

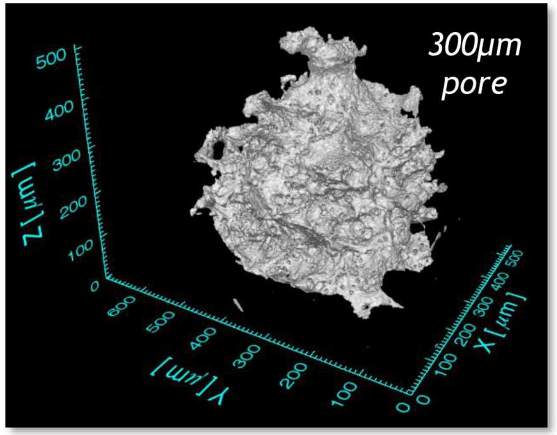
- features >60µm are easily distinguished

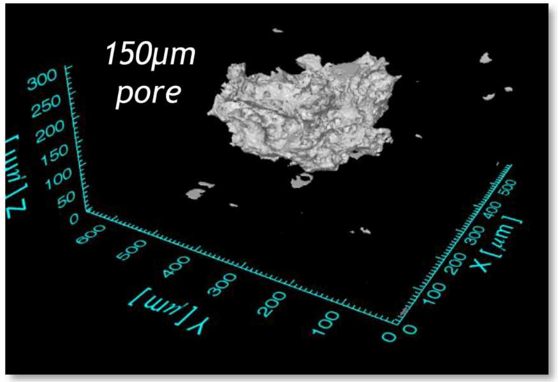
30µm feature indistinguishable from process porosity

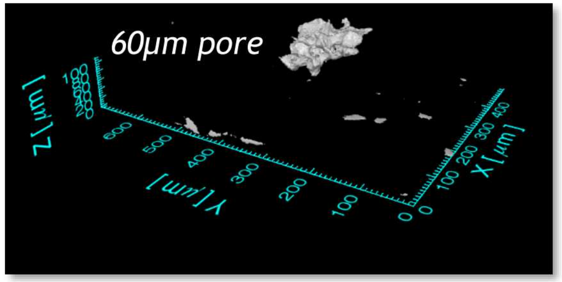
- 106 pores observed > 30µm ESD











Melt Pool Monitoring

Stratonics Therma-Viz 2-color pyrometer

- CMOS imagers: ~20μm/pixel
- 750 & 900nm filters
  - 50nm bandpass
- $\text{Temp}_{\text{pixel}} \cong \text{func}(I_{750nm}/I_{900nm})$

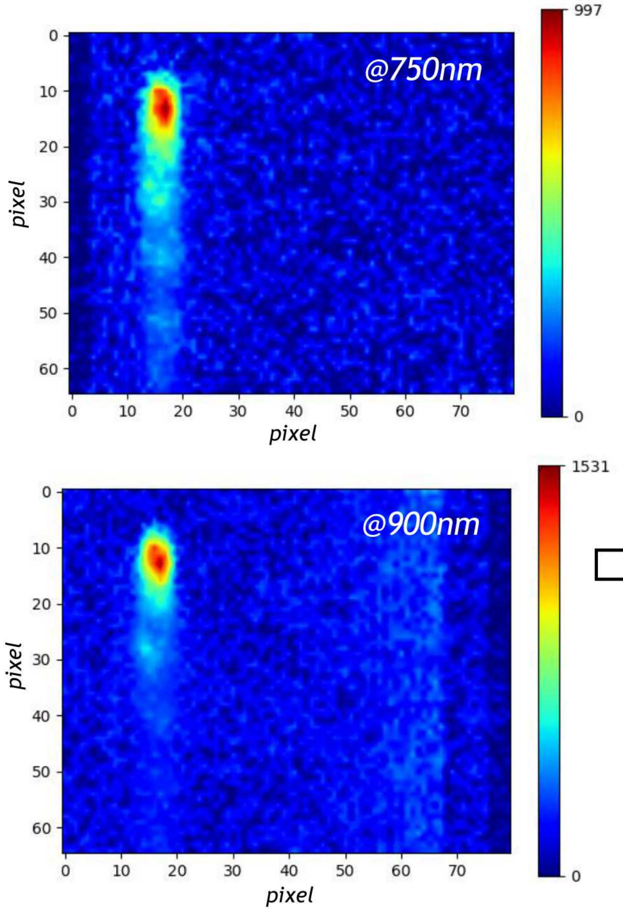
Fixed field, angled viewing

- FOV: 80 x 65 pixels (1.6 x 1.3mm)
- frame rate: 6-7kHz
  - desire >10kHz based on scan velocity

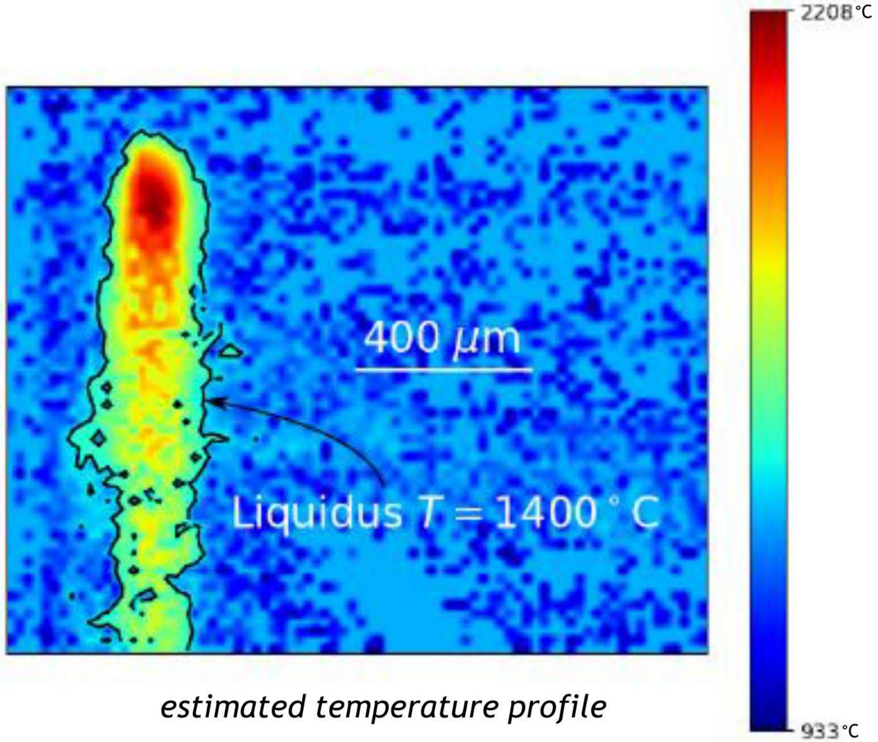
Data analysis

- 87,500 image frames per part
- custom scripts to estimate temperature

raw camera intensity

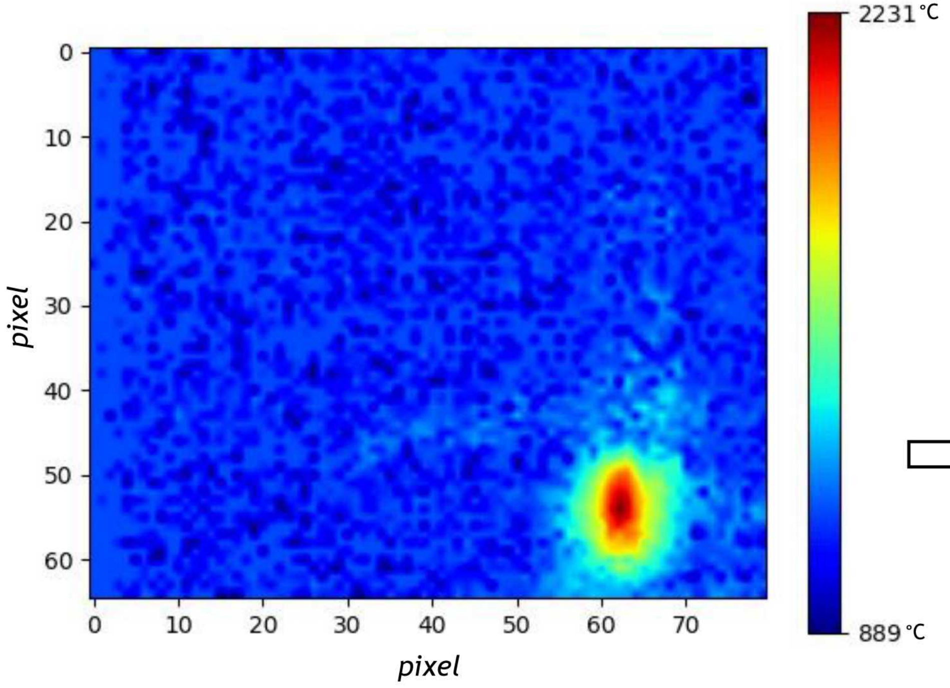


ThermaViz installed in the 3D Systems ProX 200

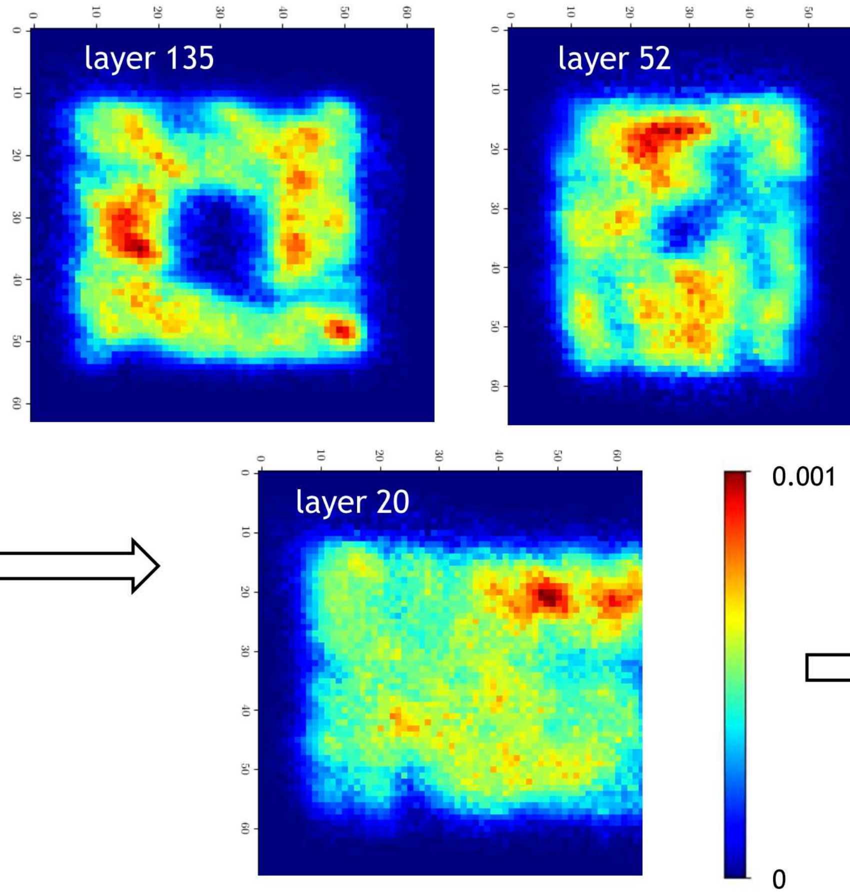


estimated temperature profile

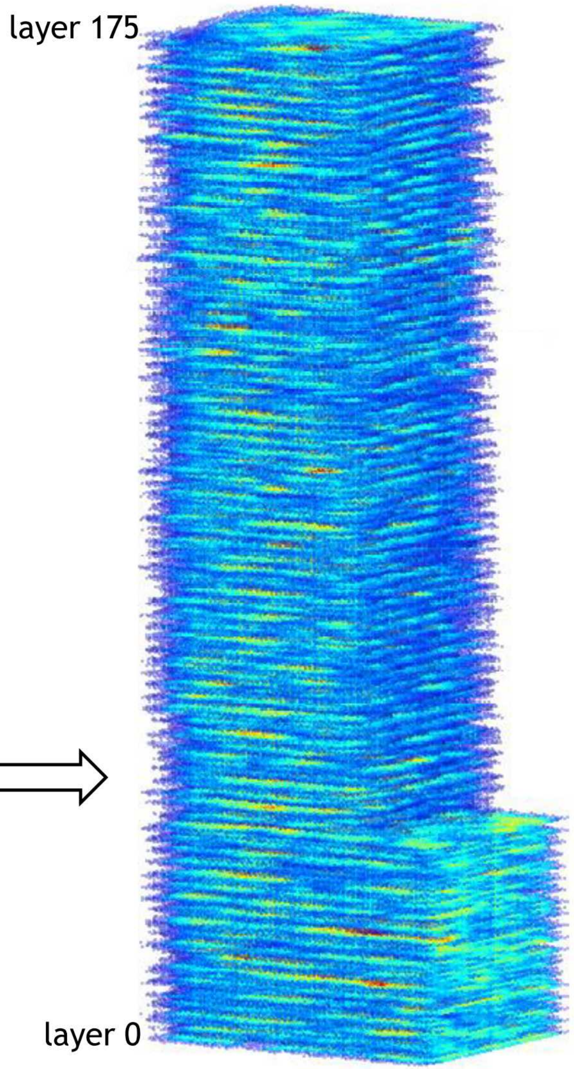
Mapping Volumetric Thermal Inputs



1) Sum temperature at every pixel in every image in an entire layer



2) Layer temperature maps are normalized to their maximum temperature sum



3) Assemble layers to generate volumetric part map

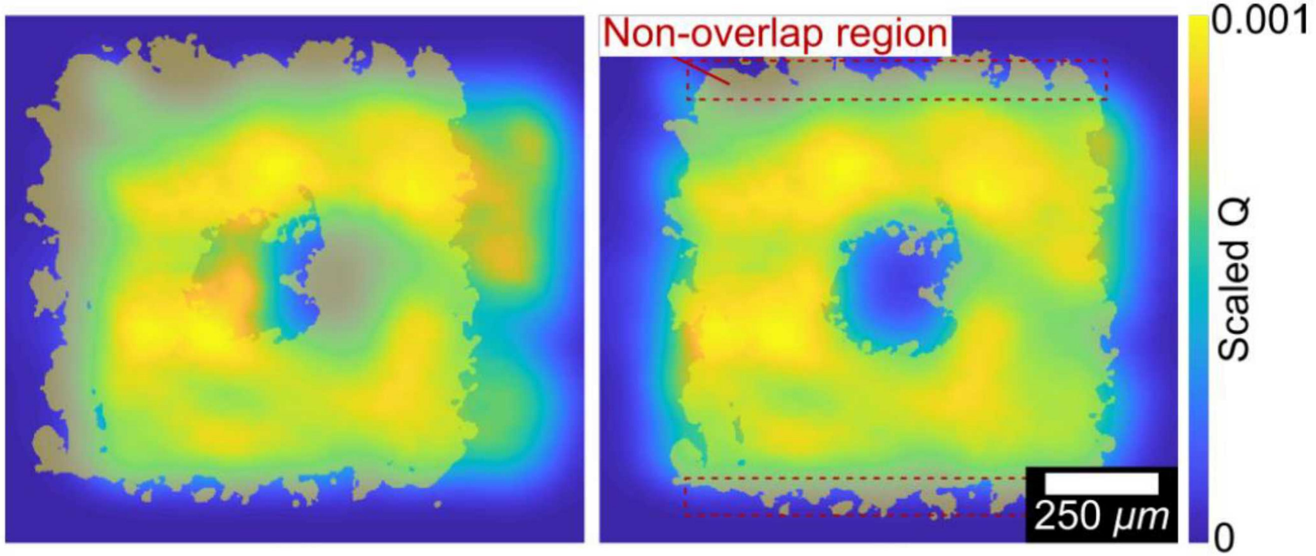
Data Registration

Disparate spatial resolutions & aspect ratios

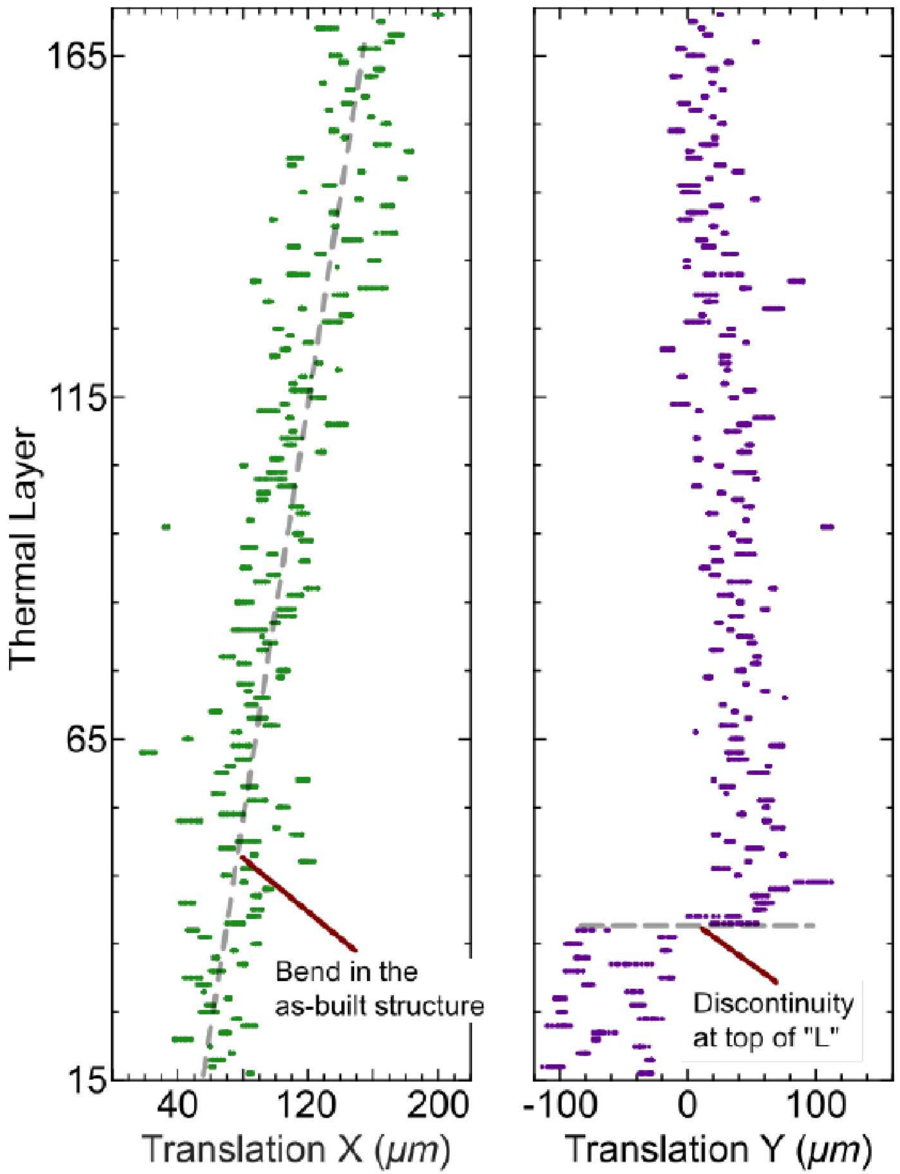
- layerwise pyrometer data scaled to μCT using bilinear interpolation

Part distortion

- requires linear translations in X & Y of pyrometer data
- top surface is “0” due to EDM build removal



overlap error near part top (left) improved after registration (right)



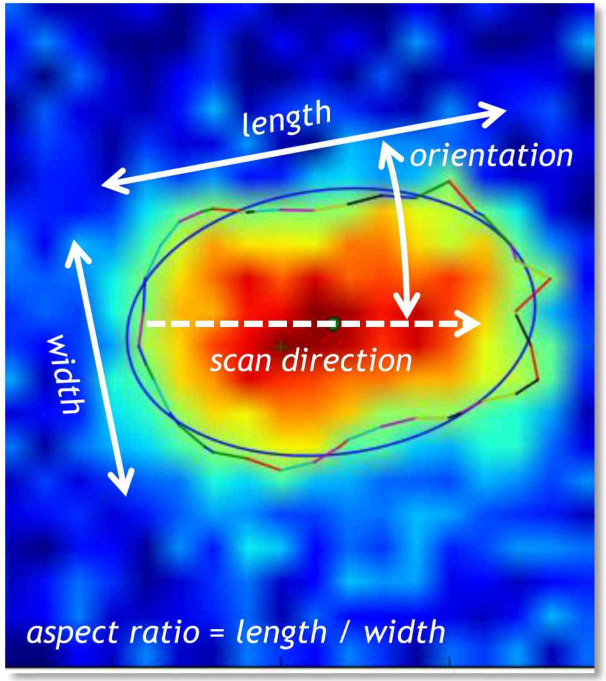
Identifying Melt Pool Outliers

Calculate melt pool characteristics (length, width, orientation, …)

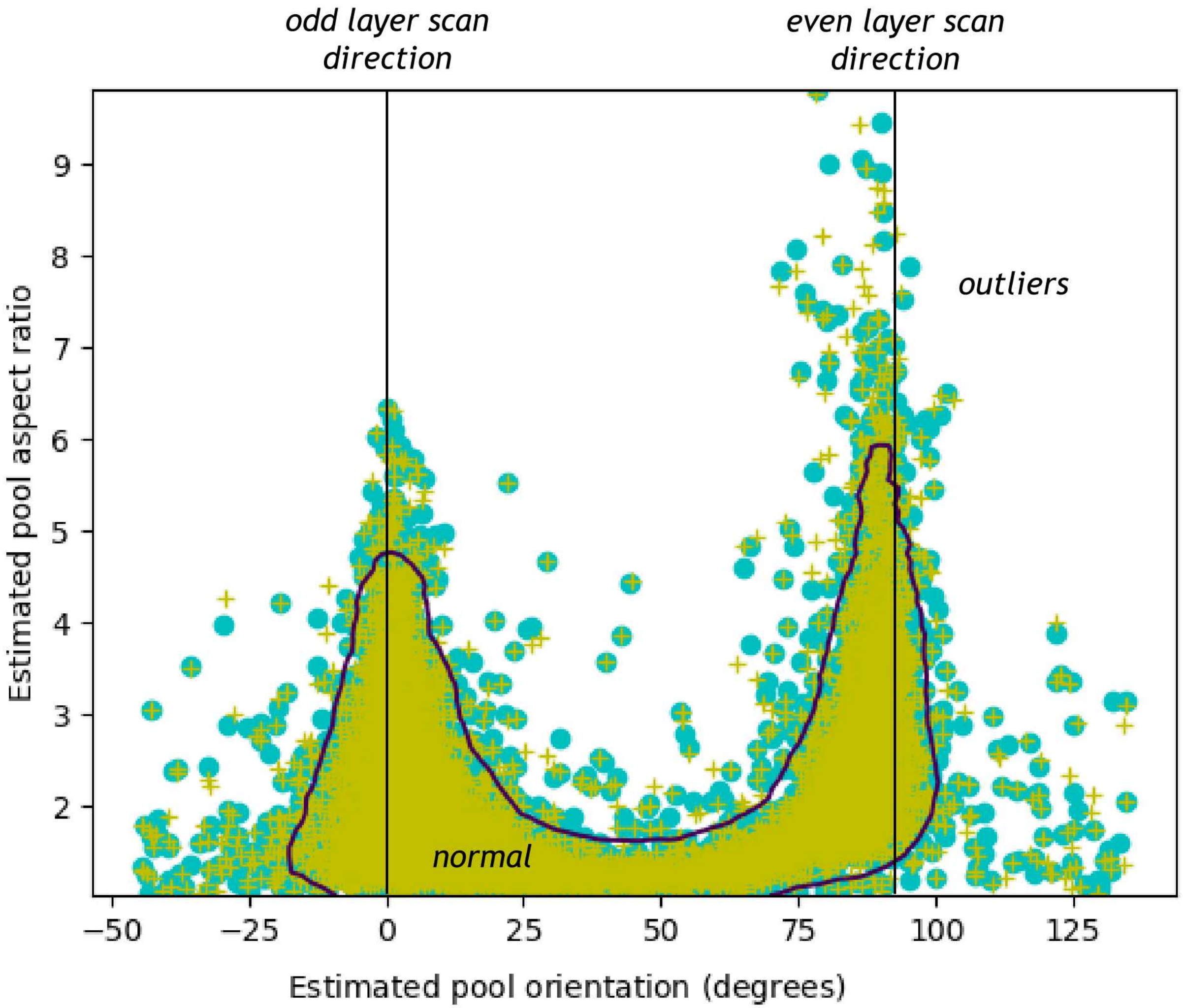
- aspect ratio vs. orientation determined valuable

Classify normal & outlier melt pools by neighbors

- outliers had <50 neighbors within a search region
- 457 outliers identified



melt pool characteristics

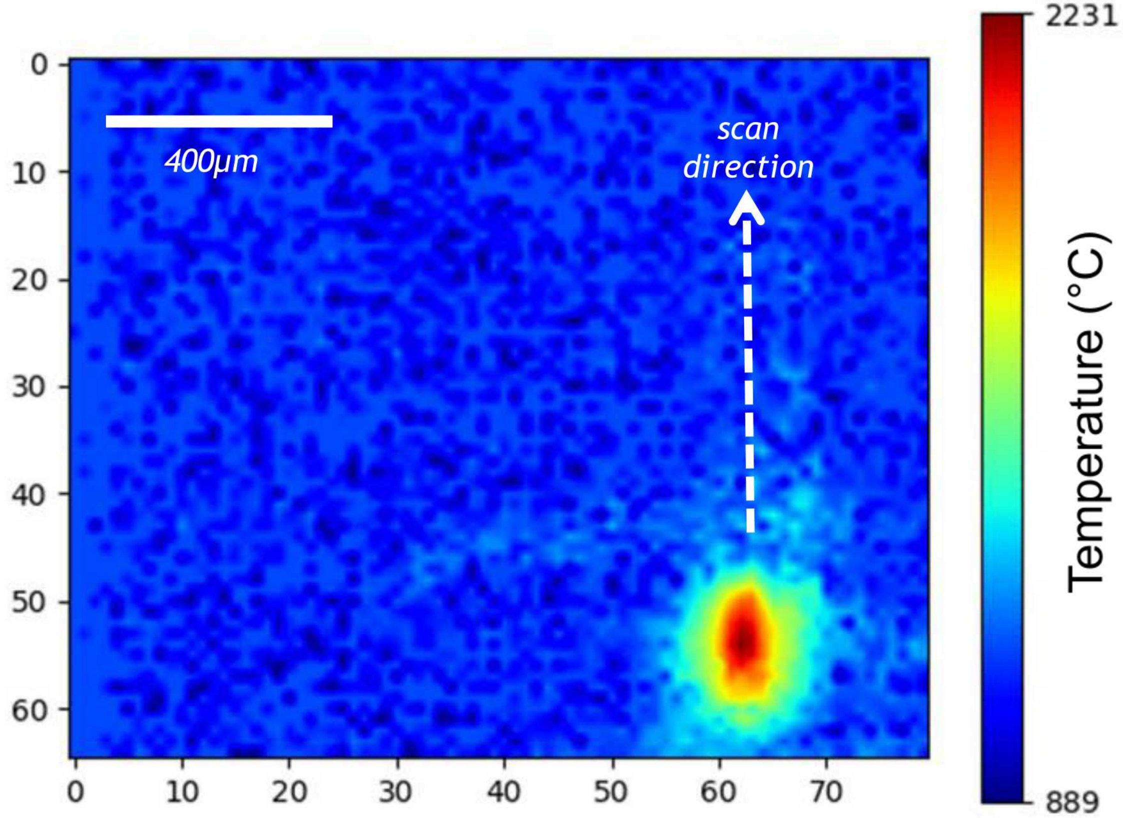


Melt Pool Outliers

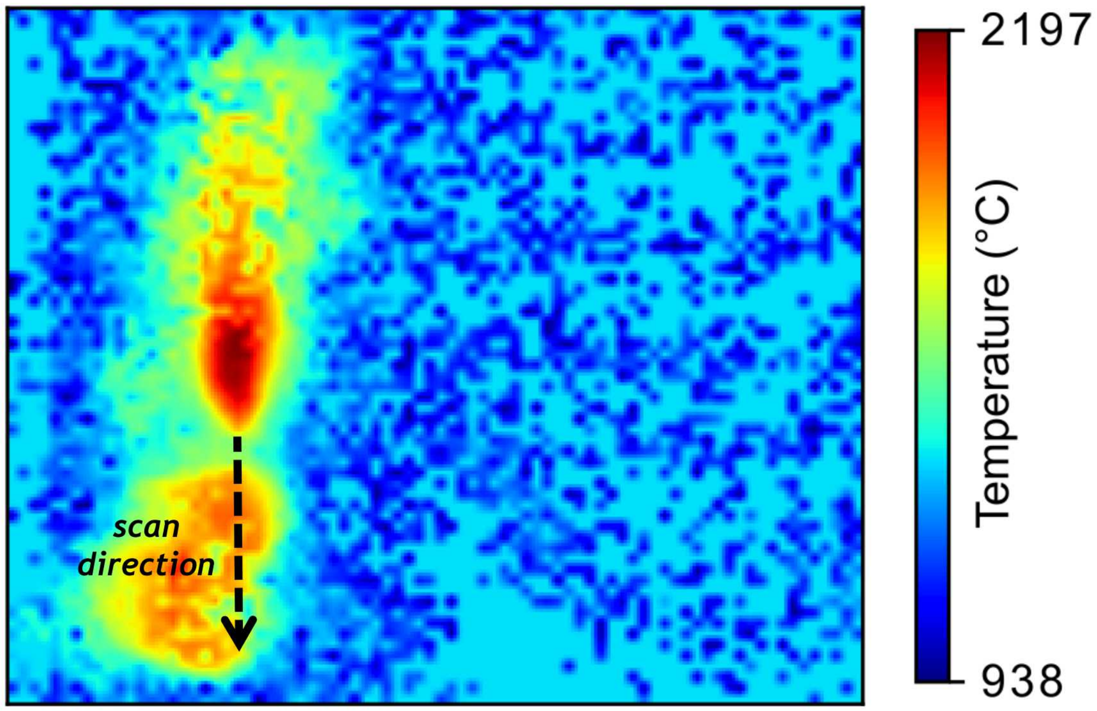
normal pools are elliptical, symmetrical & aligned to scan direction

outliers are not

- orientation angle outliers most likely signify spatter
- aspect ratio outliers most likely signify overheating / keyholing

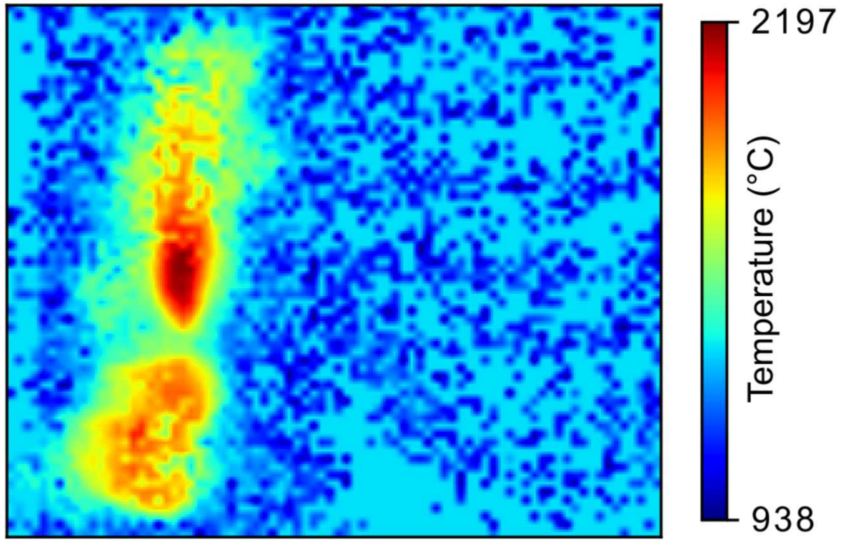


"normal" melt pool

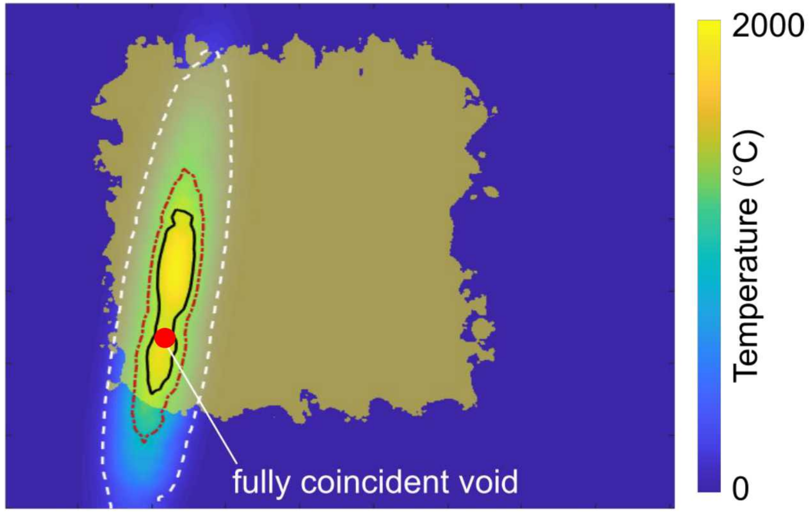


"outlier" melt pool

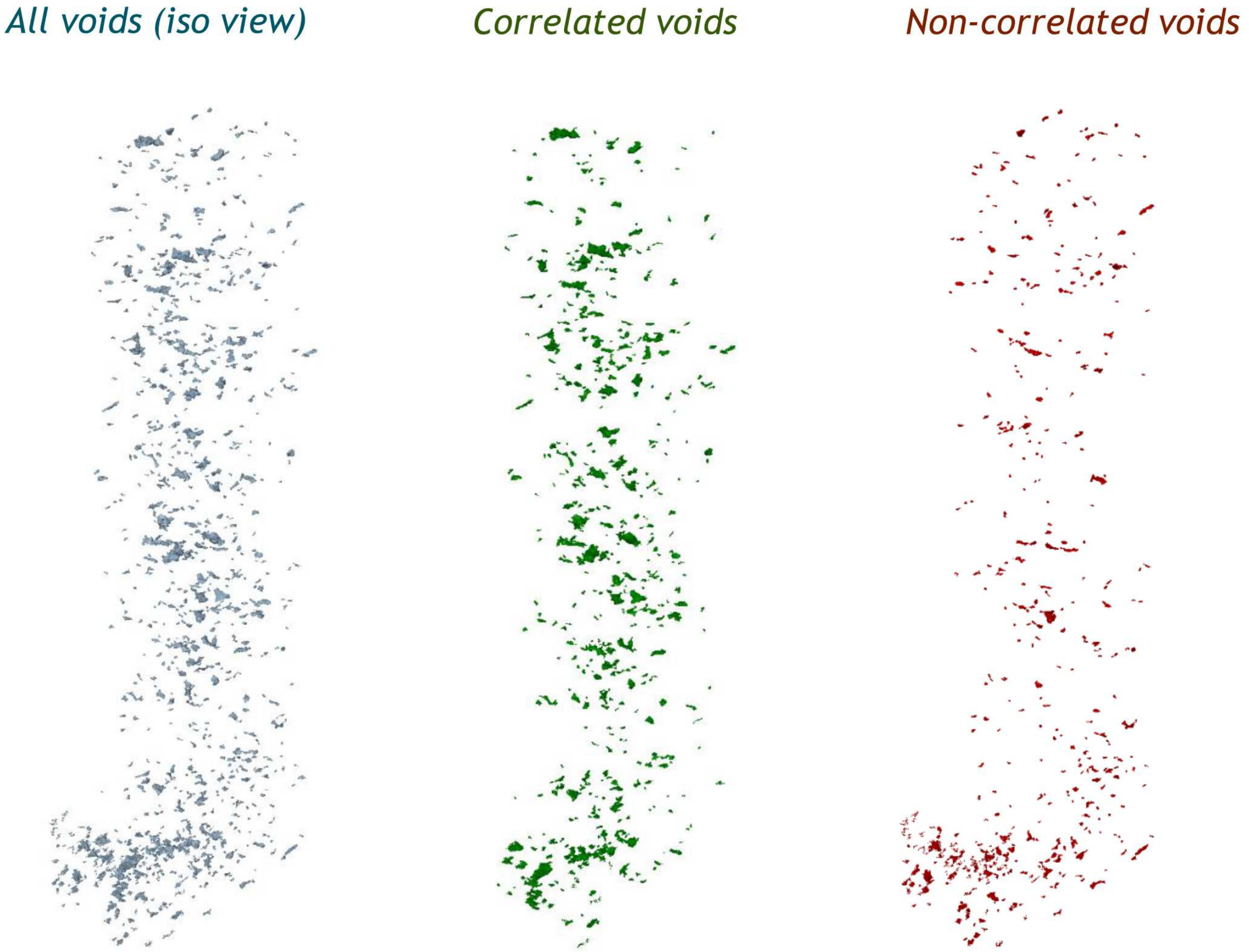
Correlating Pores w/Outlier Melt Pools



"outlier" melt pool

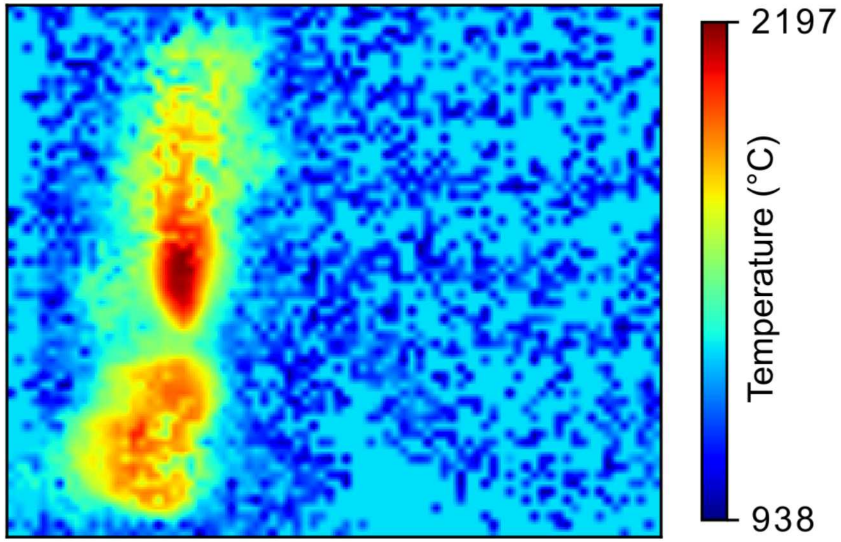


overlay of melt pool contour with pore location

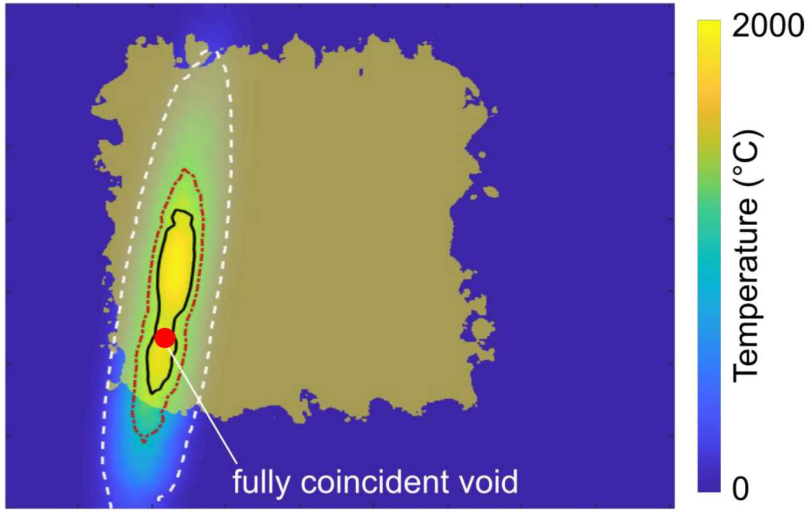


Correlation established if pore(s) is located within search region surrounding outlier melt pool

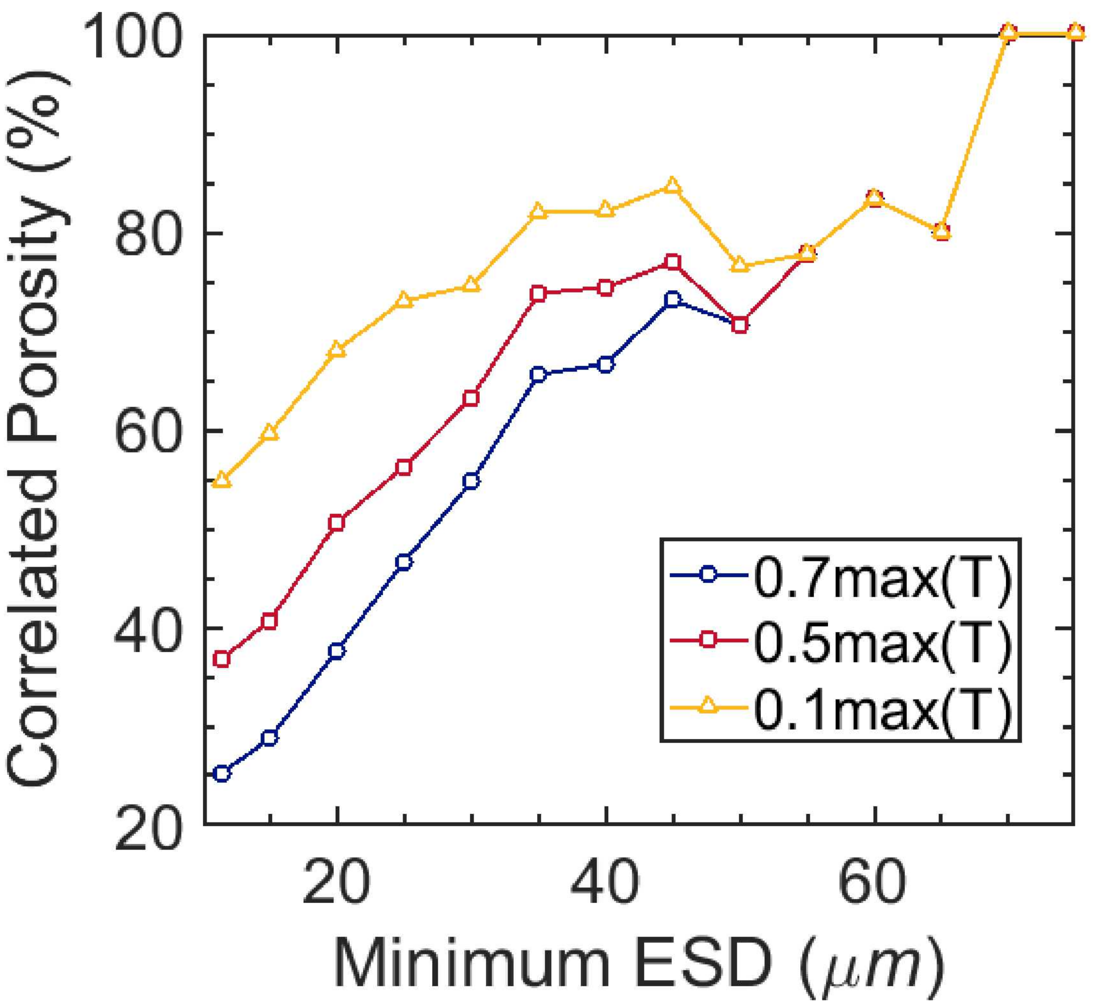
Correlating Pores w/Outlier Melt Pools



"outlier" melt pool



overlay of melt pool contour with pore location



Correlation success increases with increasing pore size

Summary

Material defects are a significant barrier to the adoption of metal AM parts

Explored feature & defect detection with two-color pyrometry & micro-CT

- tools generated for data reconstruction & analysis

Linked material porosity w/melt pool outliers

- high fidelity data (i.e. high resolution & bandwidth) is necessary
- correlations are not simple, but probabilistic in nature

Digital manufacturing requires more than an app

- data analytics are critical & represent significant investment

Questions?

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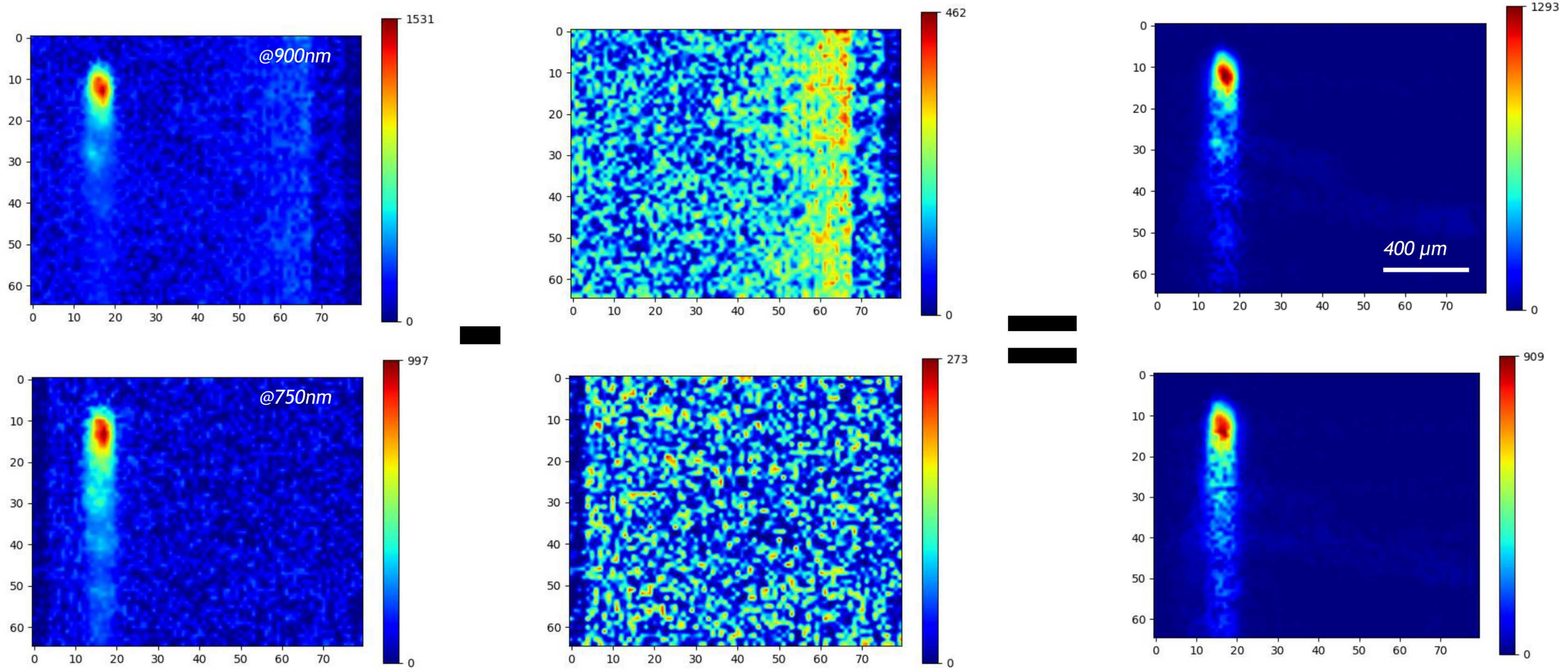
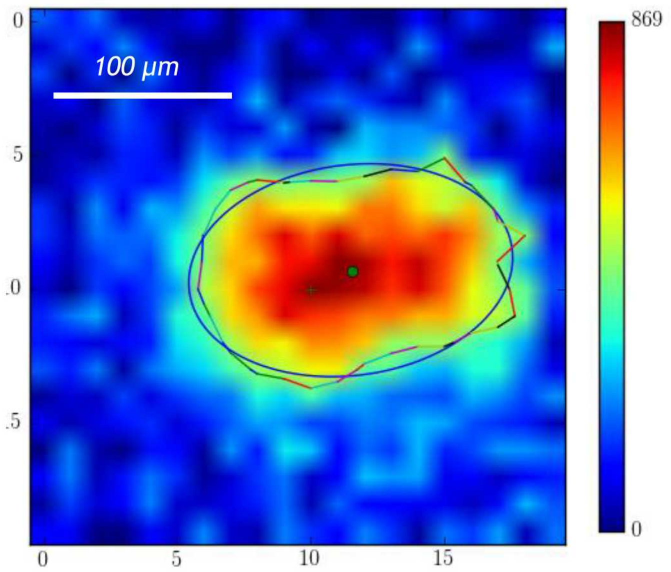
Mitchell et al, Linking Pyrometry to Porosity in Additively Manufactured Metals, Additive Mfg, in process

Pyrometer Data Processing: Background Removal

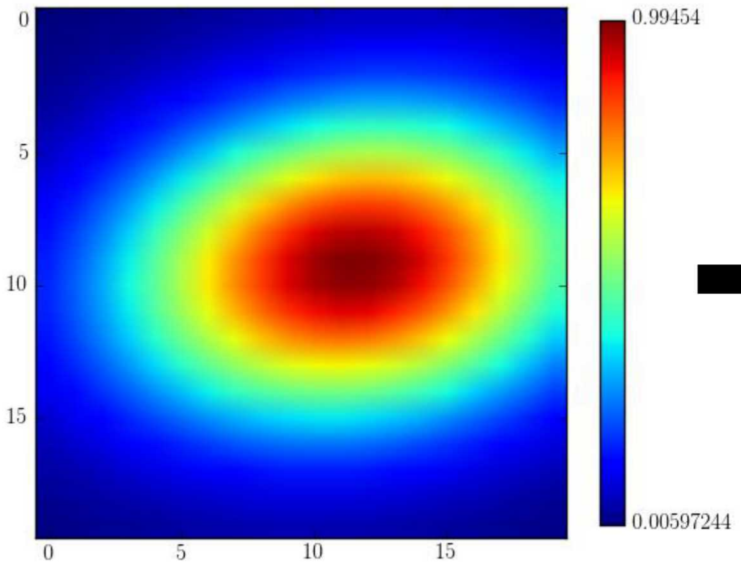


raw images *background, laser off* *images w/background removed*

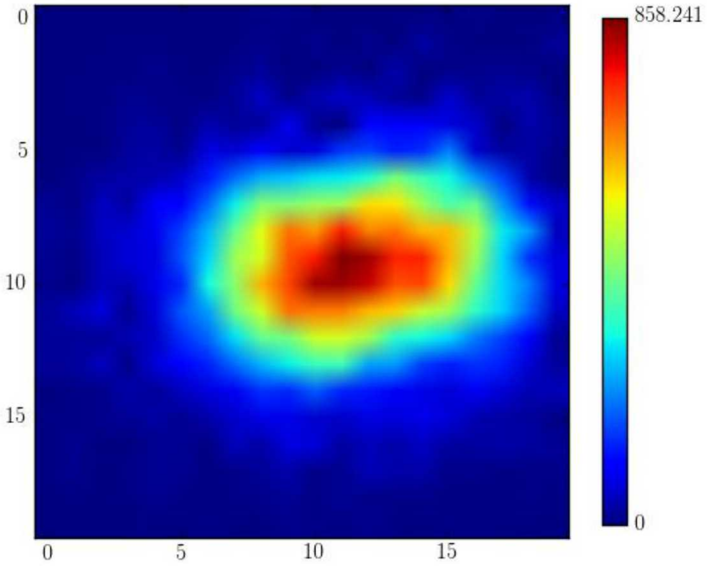
Pyrometer Data Processing: Contour & Best Fit Ellipse



marching squares contour to raw image

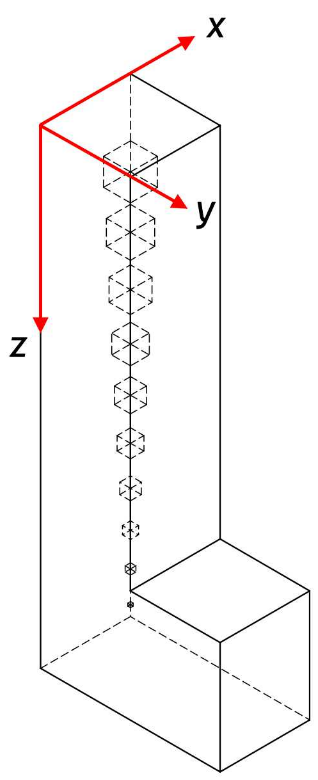


Gaussian profile based on direct least squares ellipse fit

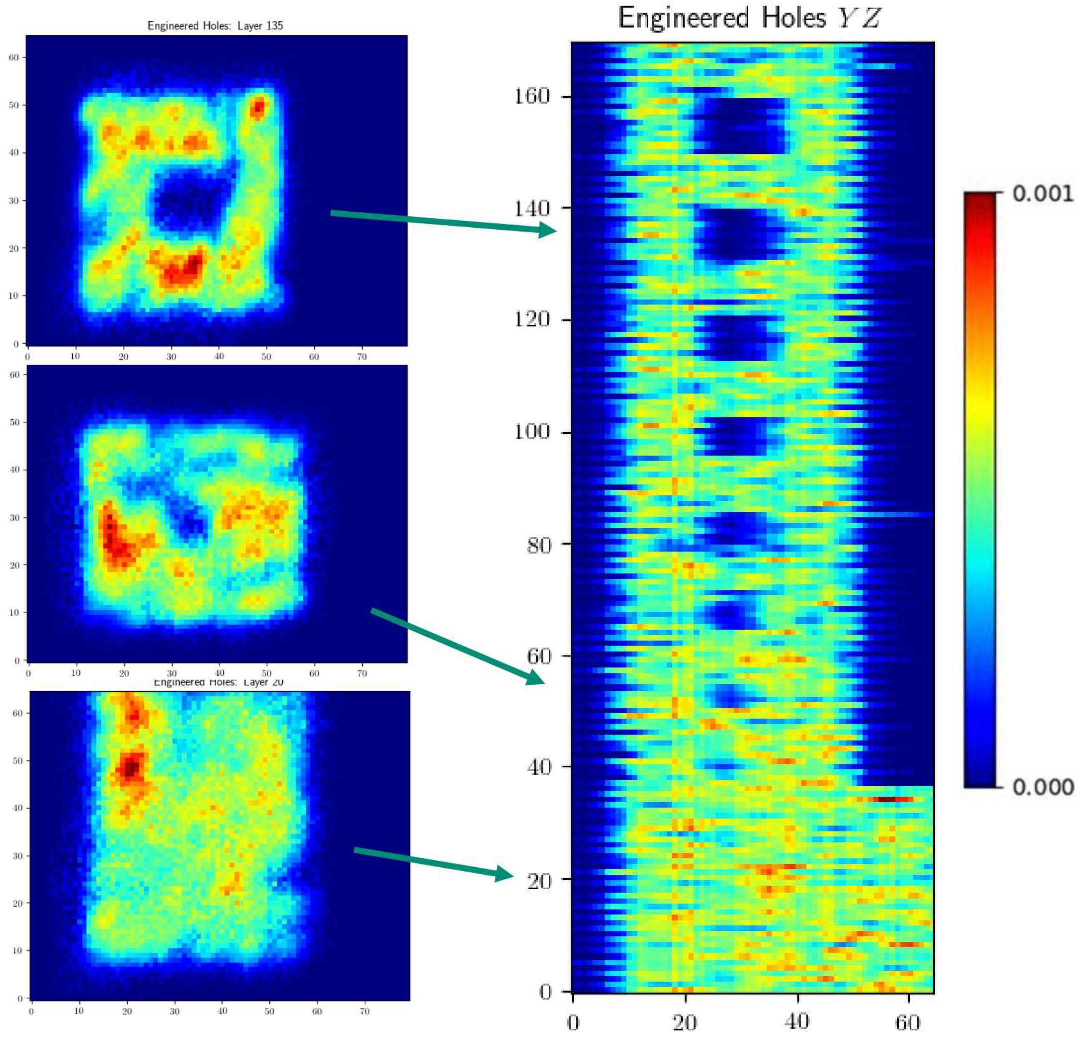


Gaussian filter applied

Mapping Volumetric Thermal Inputs



captured holes design



normalized pyrometer data summed at each voxel, layers (left) & XZ volume section (right)

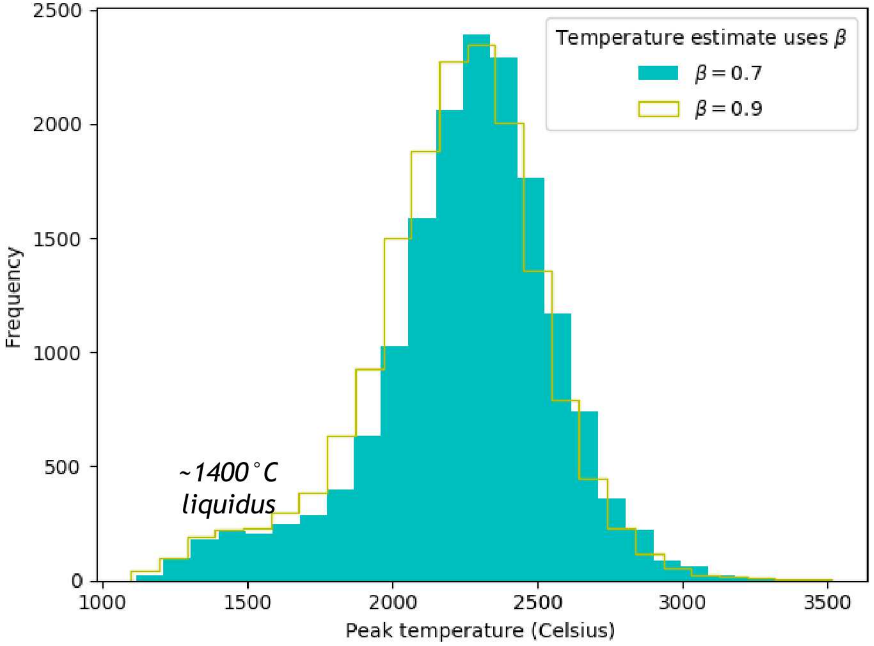
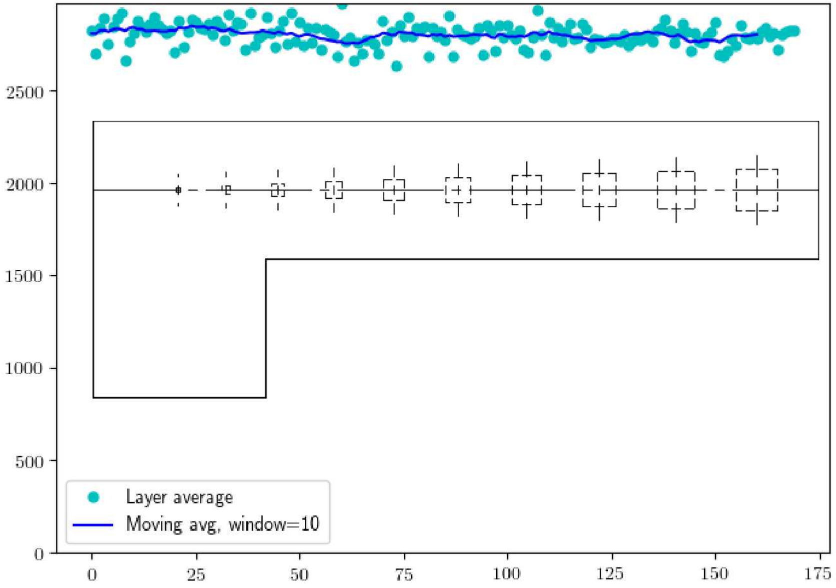
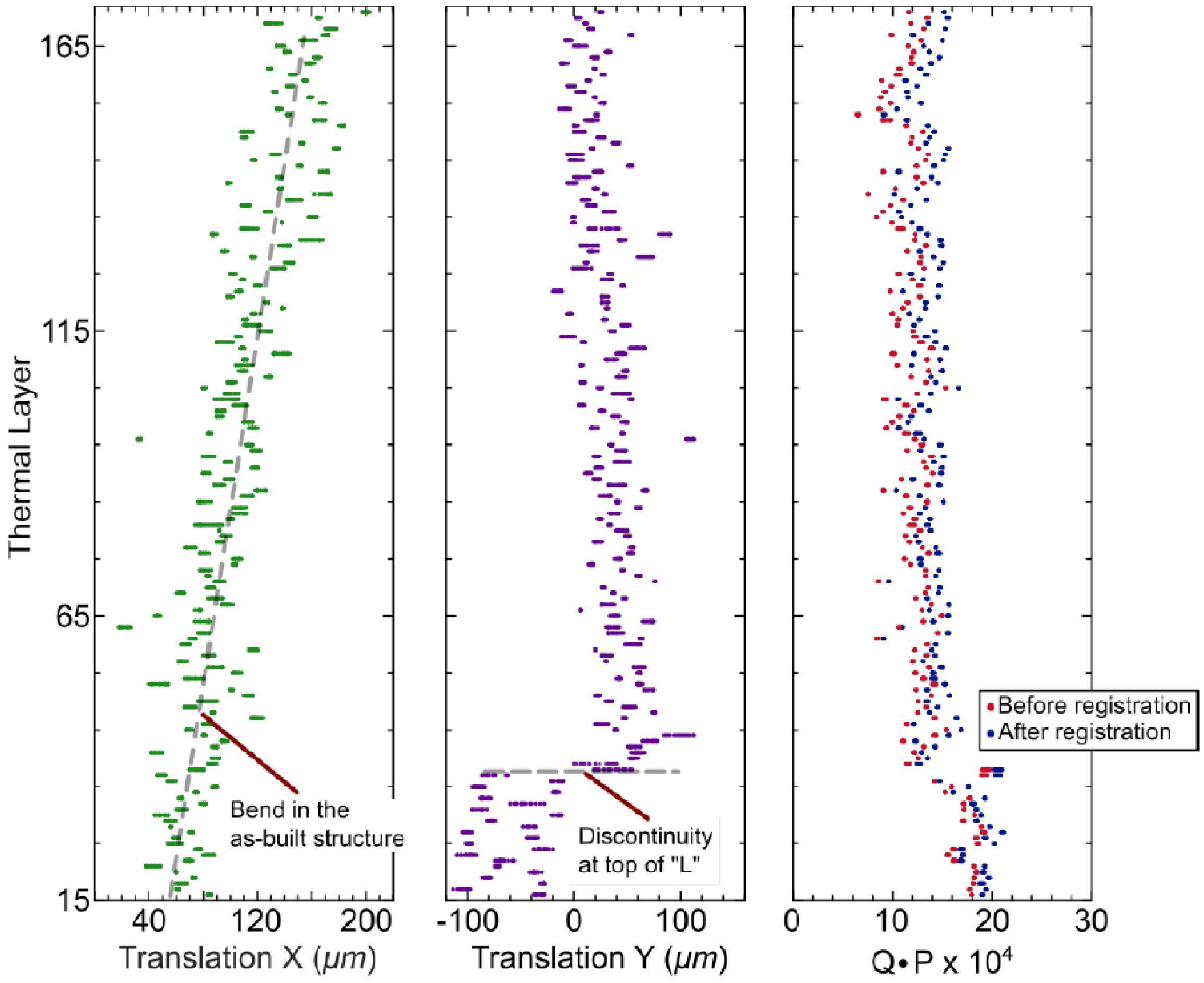


image peak temperature histogram



average image peak temperature per build layer

Pyrometry Data Translations



Correlation Statistics

Minimum ESD (μm)	11.4	20	30	40	50	60	70
Thresh $0.1T_p$	55%	68%	75%	82%	77%	83%	100%
Thresh $0.5T_p$	37%	51%	63%	74%	71%	83%	100%
Thresh $0.7T_p$	25%	38%	55%	67%	71%	83%	100%
Total # Pores	966	310	106	39	17	6	2

percentage of pores spatially correlated with outlier melt pools

	False positive melt pools	Coincident melt pools	False positive rate
Thresh $0.1T_p$	105	352	23%
Thresh $0.5T_p$	204	253	45%
Thresh $0.7T_p$	265	192	58%

number of melt pools coincident & non-coincident (false positives) w/unintentional pores

	Total #	# > 30μm ESD
Total	966	106
Correlated to outlier MP	516	81
Not correlated	450	25