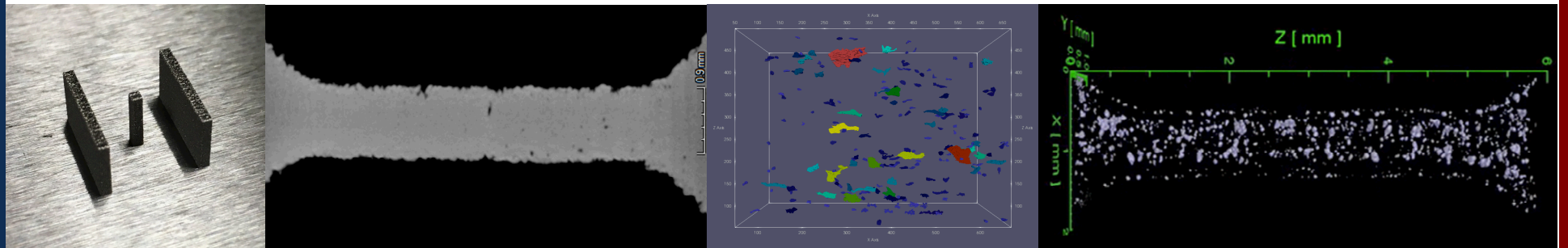


# Defect Signatures for Metal Laser Powder Bed Fusion

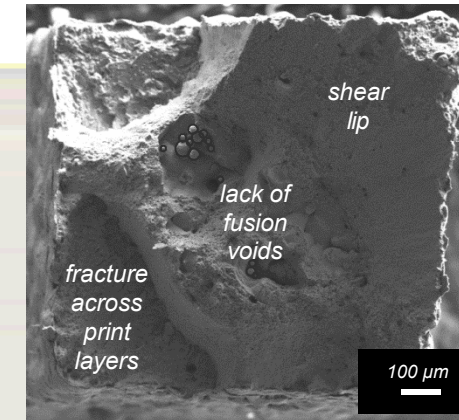
Bradley Jared, Jon Madison, Thomas Ivanoff, John Mitchell, Erich Schwaller, Josh Koepke, Laura Swiler, David Saiz, Kevin Webb, Jeff Rodelas



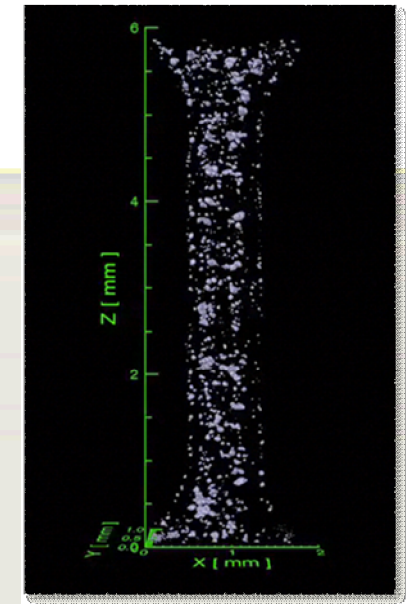


# Material Assurance

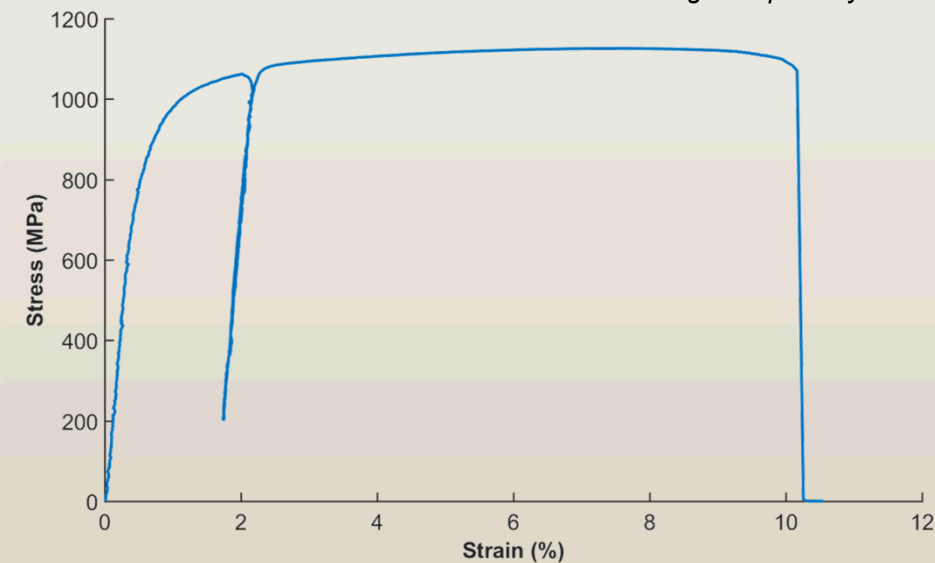
- Material formation concurrent w/geometry
  - want to predict part/material performance
  - **how to ID a bad part?**
    - complexity isn't "free"
    - requires significant design margins and/or rigorous post-process inspection / validation
- Quantify critical material defects & useful signatures
  - D-tests, NDE, process monitoring, mod-sim, ?
- Understand mechanistic impacts on properties
  - build process-structure-property relationships to predict margins & reliability
  - characterize stochastic response to design for uncertainties
  - provide scientific basis for qualification of AM metals for high consequence applications



17-4PH dogbone fracture surface



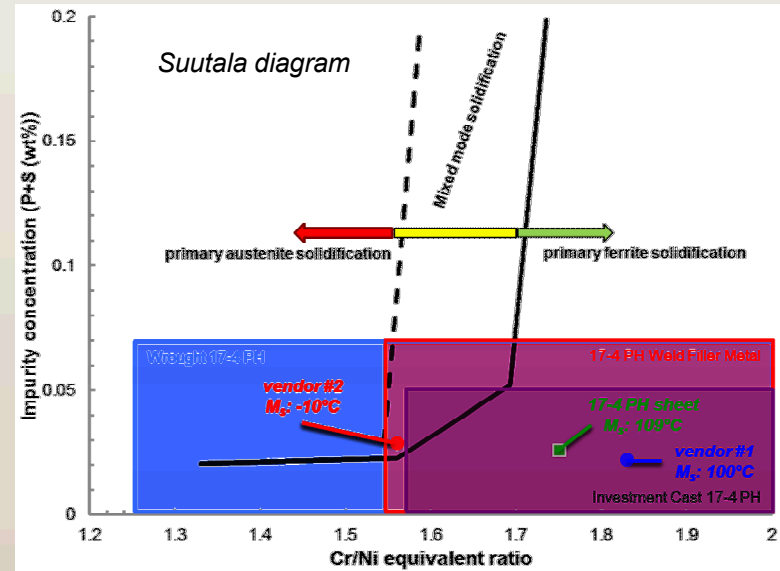
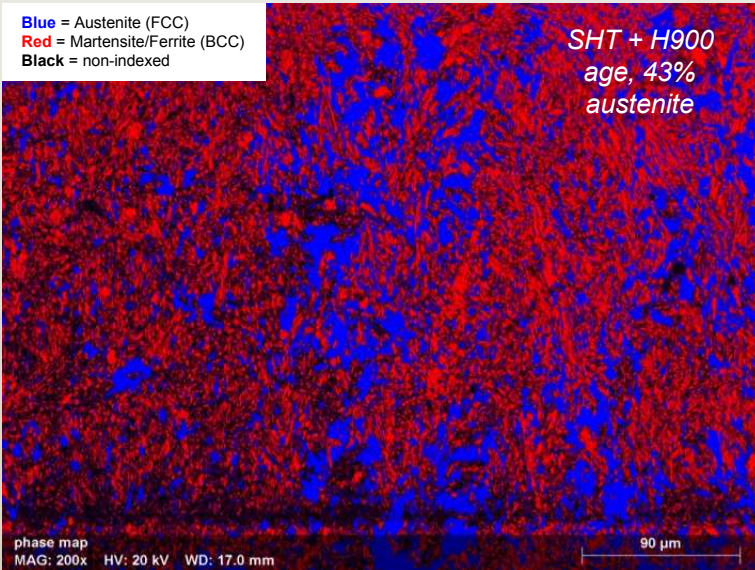
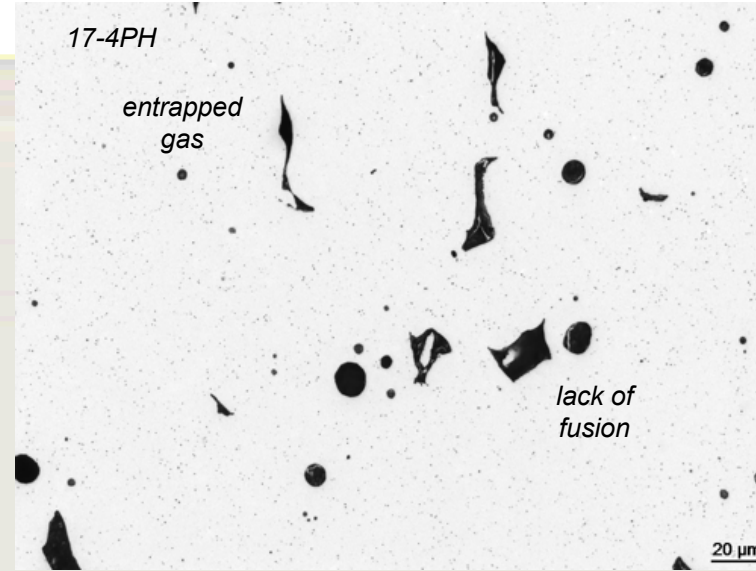
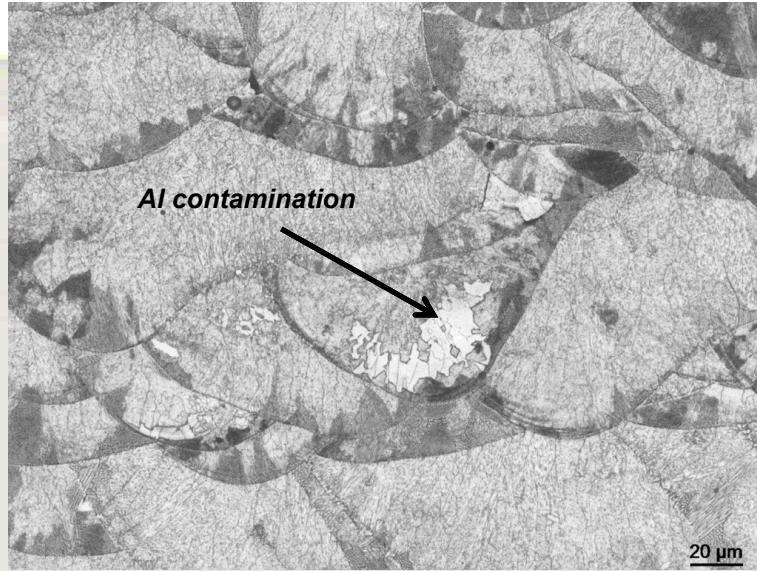
17-4PH dogbone porosity



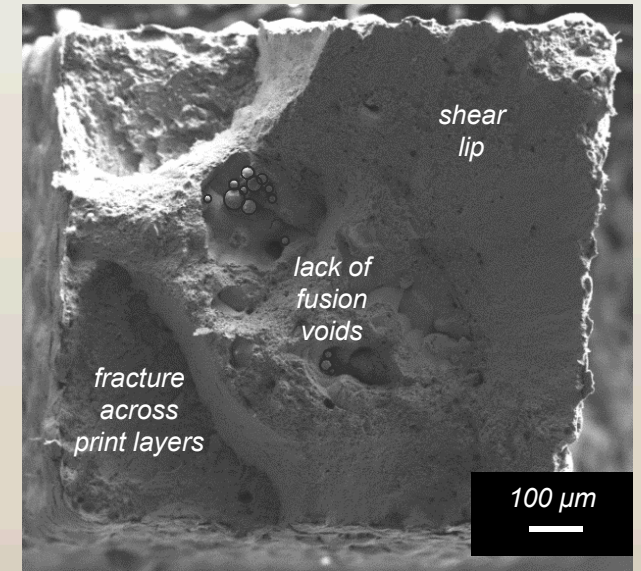
17-4PH dogbone stress-strain response



# Representative Material Defects



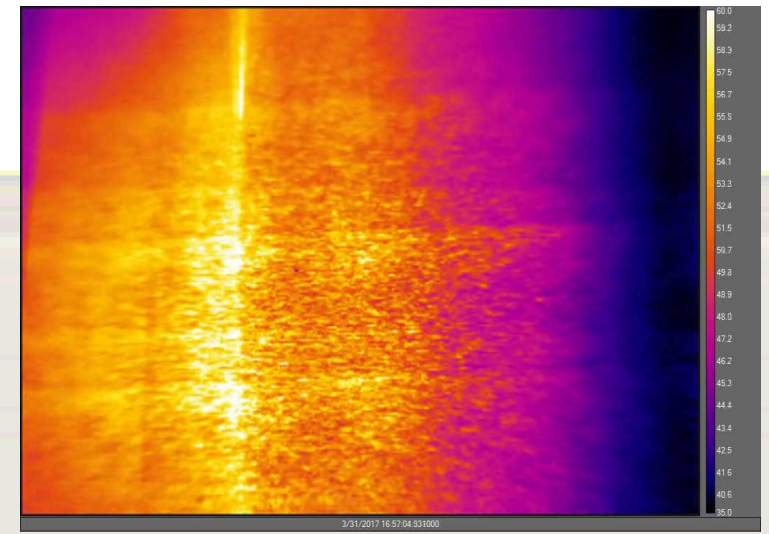
defect  
 dominated  
 failure, 2%  
 elongation,  
 17-4PH





# Pursuing In-Situ Signatures

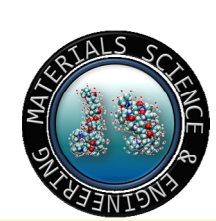
- 3D Systems ProX 200
  - 3D Systems Open Protocol platform
- Thermal
  - Stratonics ThermaViz two-color pyrometer
  - IR cameras: FLIR C2, A310 & SC6811
- Optical
  - Photron PhotoCam Speeder V2 high speed cameras
    - blue light illumination
  - Ocean Optics LIBS2500plus spectrometer
  - Keyence LJ-V7020 & LJ-V7200 laser line scanners
- Acoustic
  - audio microphone, acoustic emission
- Laser characterization
  - Ophir Spiricon SP928 beam profiler
  - Ophir L50(300)A-LP1 power meter



FLIR A310, laser on plate, ~100W, 1.4m/sec, 125µm hatch, 100µm beam dia.

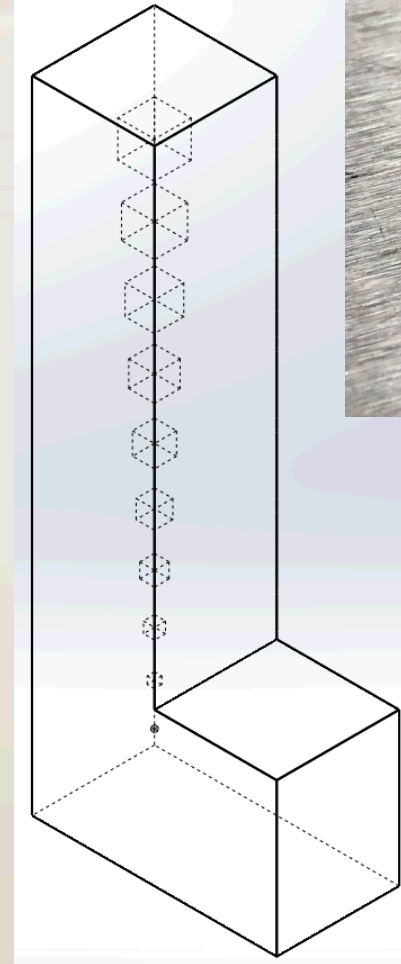


Photron high speed optical melt pool video

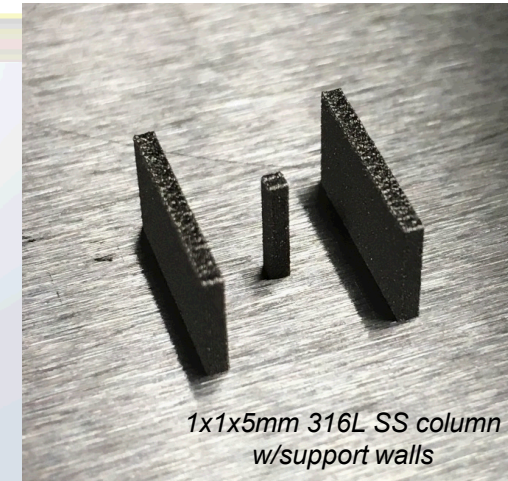


# Intentional Porosity Structure

- Introduced intentional pores
  - 316L stainless steel
  - 1-10 layer thickness
    - 30-300 $\mu\text{m}$
  - 1x1x5.25mm column
    - 175 layers
    - 87,500 T-V frames per part
- Tests are quick
  - data analysis is not...
  - seek to correlate spatial sensor data (X,Y,Z,time) to material porosity (X,Y,Z)



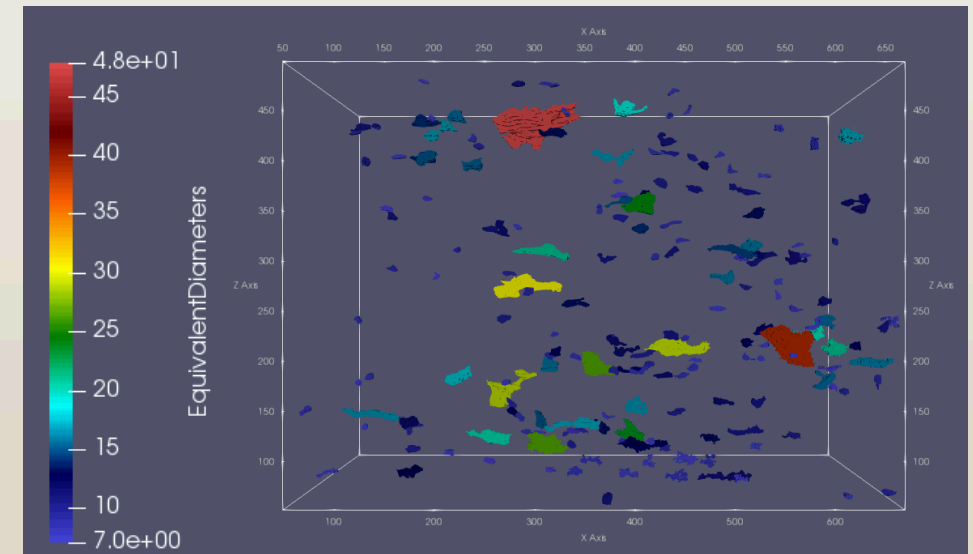
*captured hole structure*



*1x1x5mm 316L SS column  
w/support walls*



*captured defect holes part CT image, Zeiss  
Xradia 520 Versa, voxel resolution ~ 2 $\mu\text{m}$ ,  
Harlan Brown-Shaklee*



*porosity map generated using DREAM.3D near the 10 & 20 $\mu\text{m}$  pores*



# Material Reconstruction

**VOLUME GRAPHICS**  
Micro-computed tomography

**MATLAB**  
Interactive Data Language

**IDL**

**Adobe Photoshop**

**Ps**

batch processing  
16bit > 8bit conversion  
lossless filetype conversion

**FIJI**

alignment & registration  
cropping  
grayscale matching  
autoleveling  
image filtering  
thresholding

3D reconstruction  
3D quantification

**ParaView**  
Parallel Visualization Application

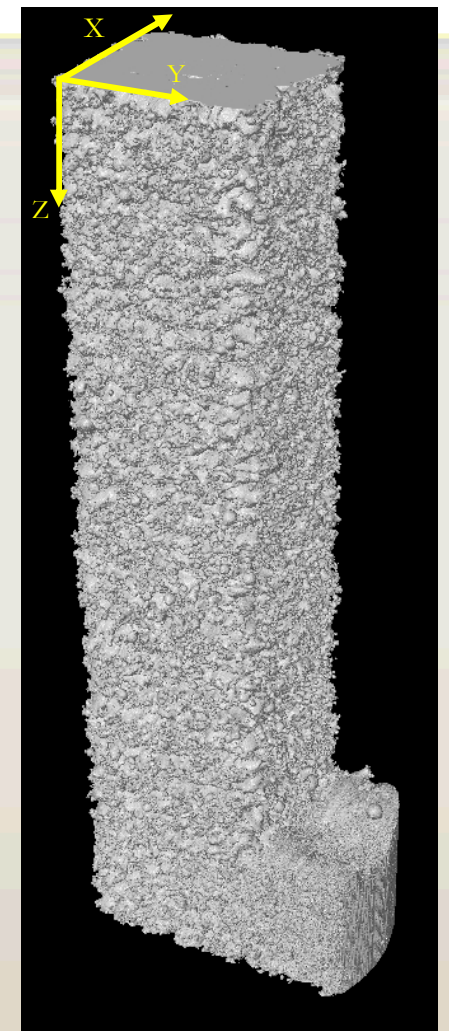
**DREAM.3D**

image processing & quantification. 3D reconstructions

**BlueQuartz Software**  
Specializing in Software Tools for the Scientist  
<http://dream3d.bluequartz.net>

**ROBO-MET.3D™**  
A USB PRODUCT

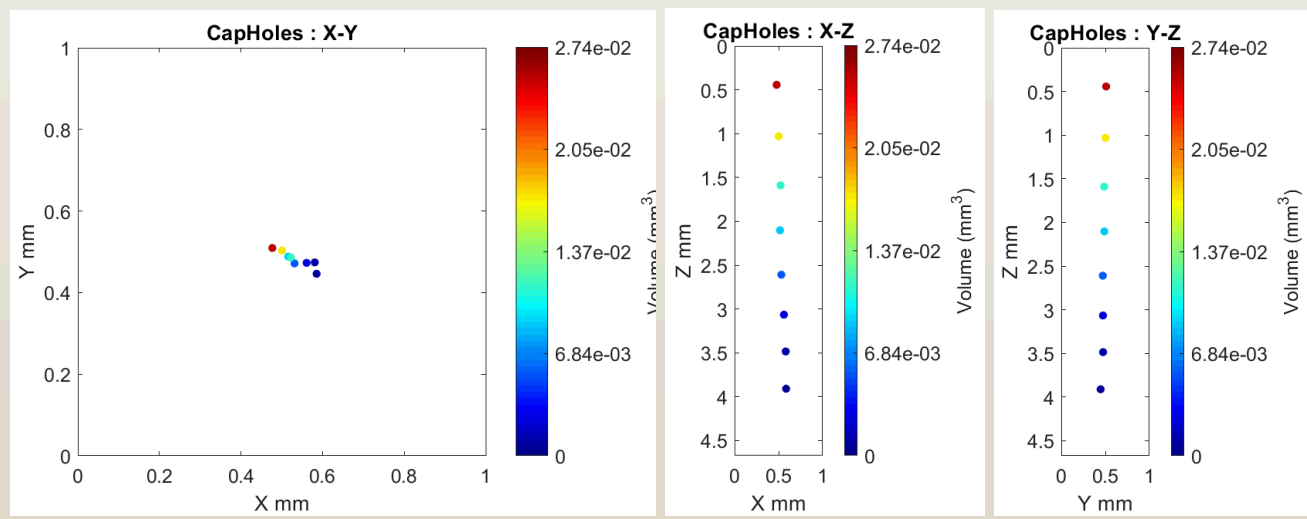
Serial-sectioning



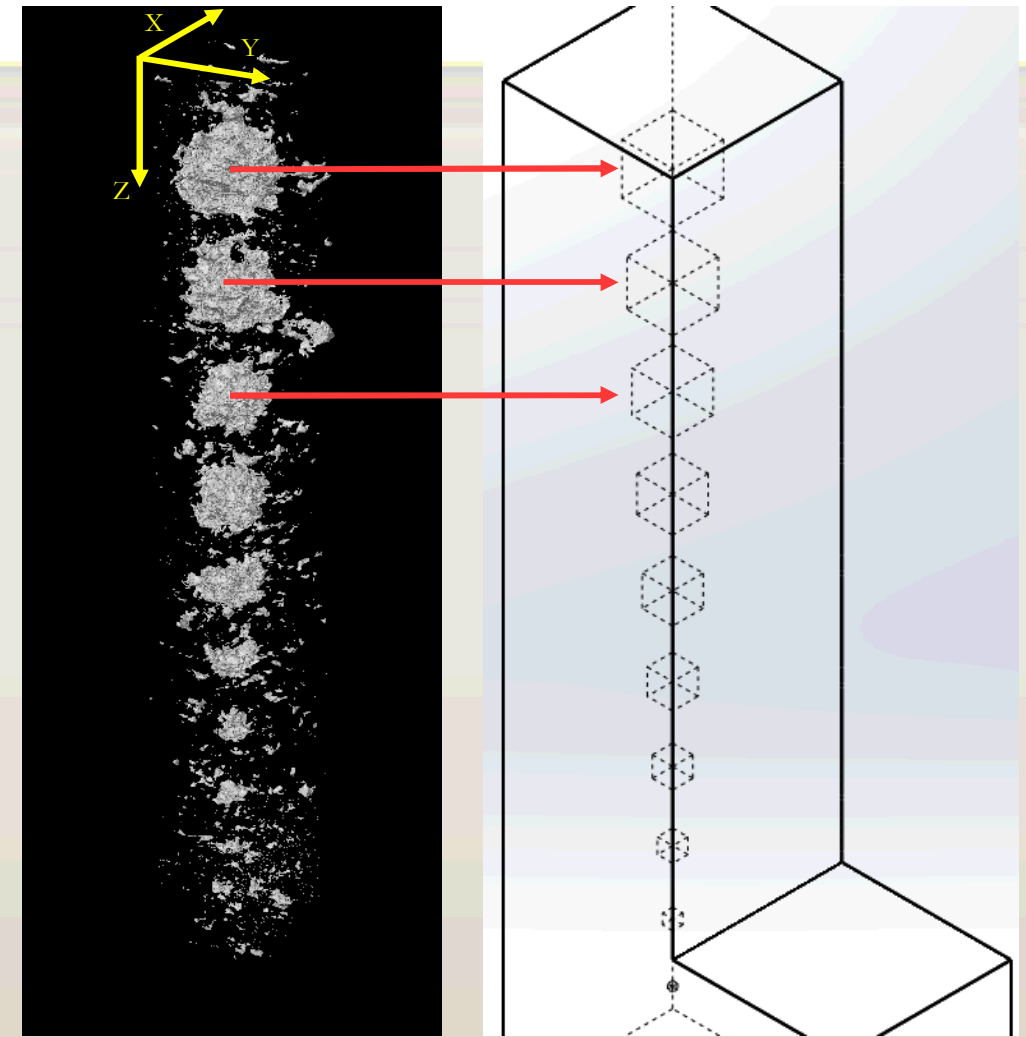


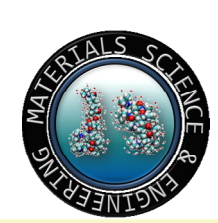
# $\mu$ CT Data Registration

- Rough surfaces create challenges
- Registering pore structures to nominal design
  - calculate top three hole centroid locations
  - calculate  $\Delta(x,y,z)$  from design locations
  - remove slope & offsets



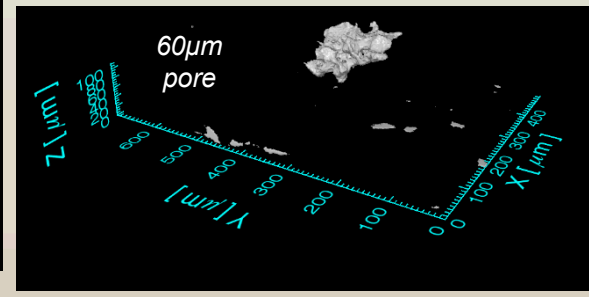
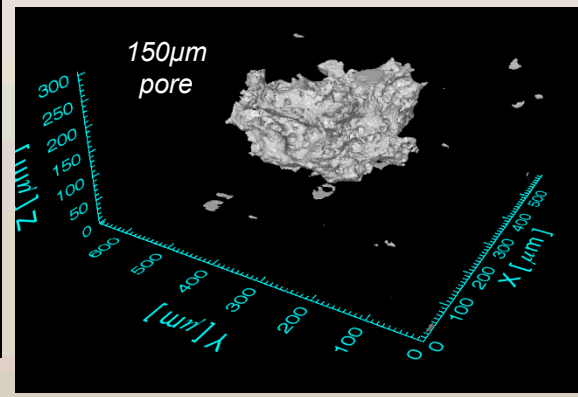
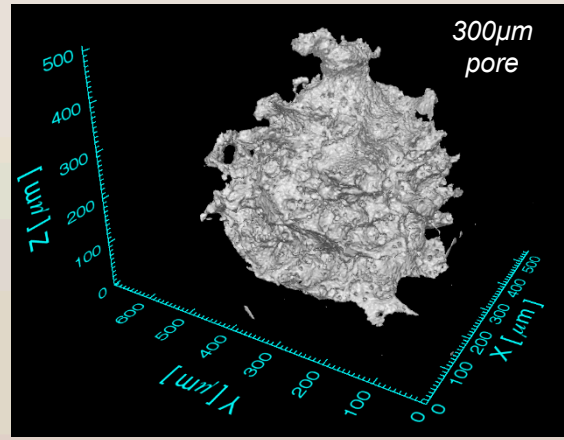
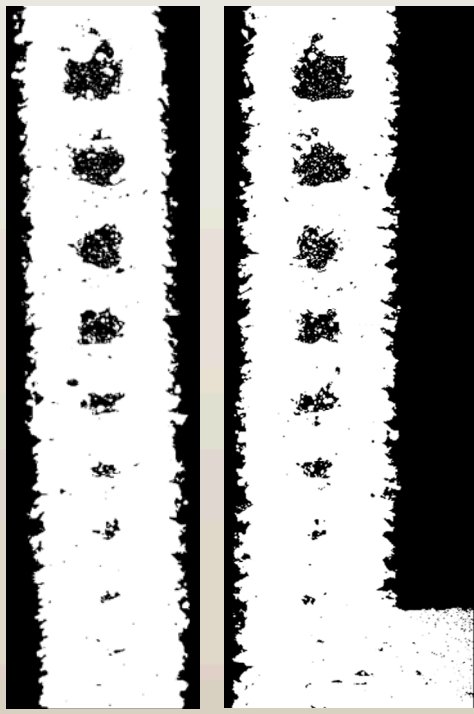
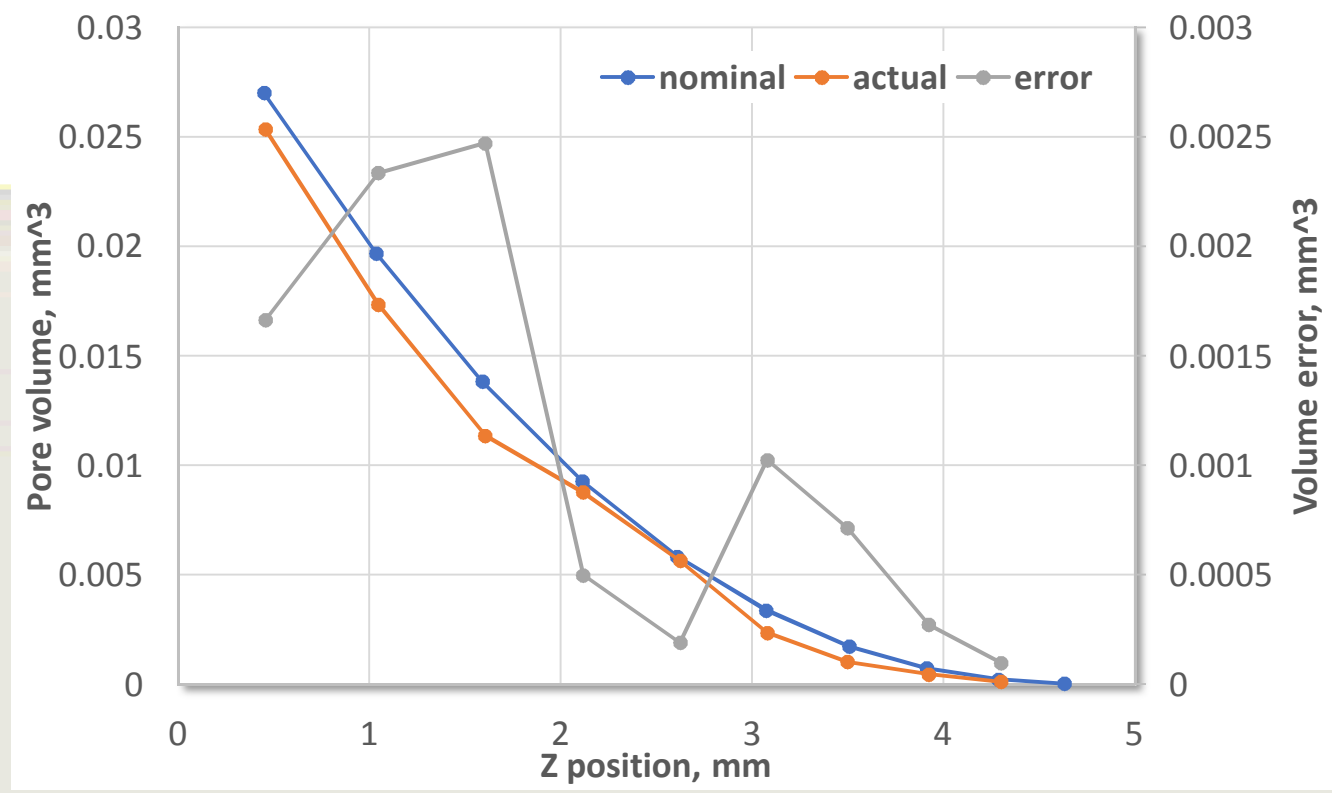
*intentional pore locations showing data misalignment*

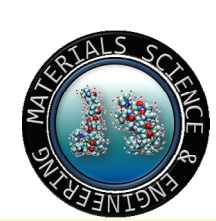




# Pore Identification

- Largest 9 pores easily distinguished by volume
- 30 $\mu$ m pore indistinguishable from process porosity by size



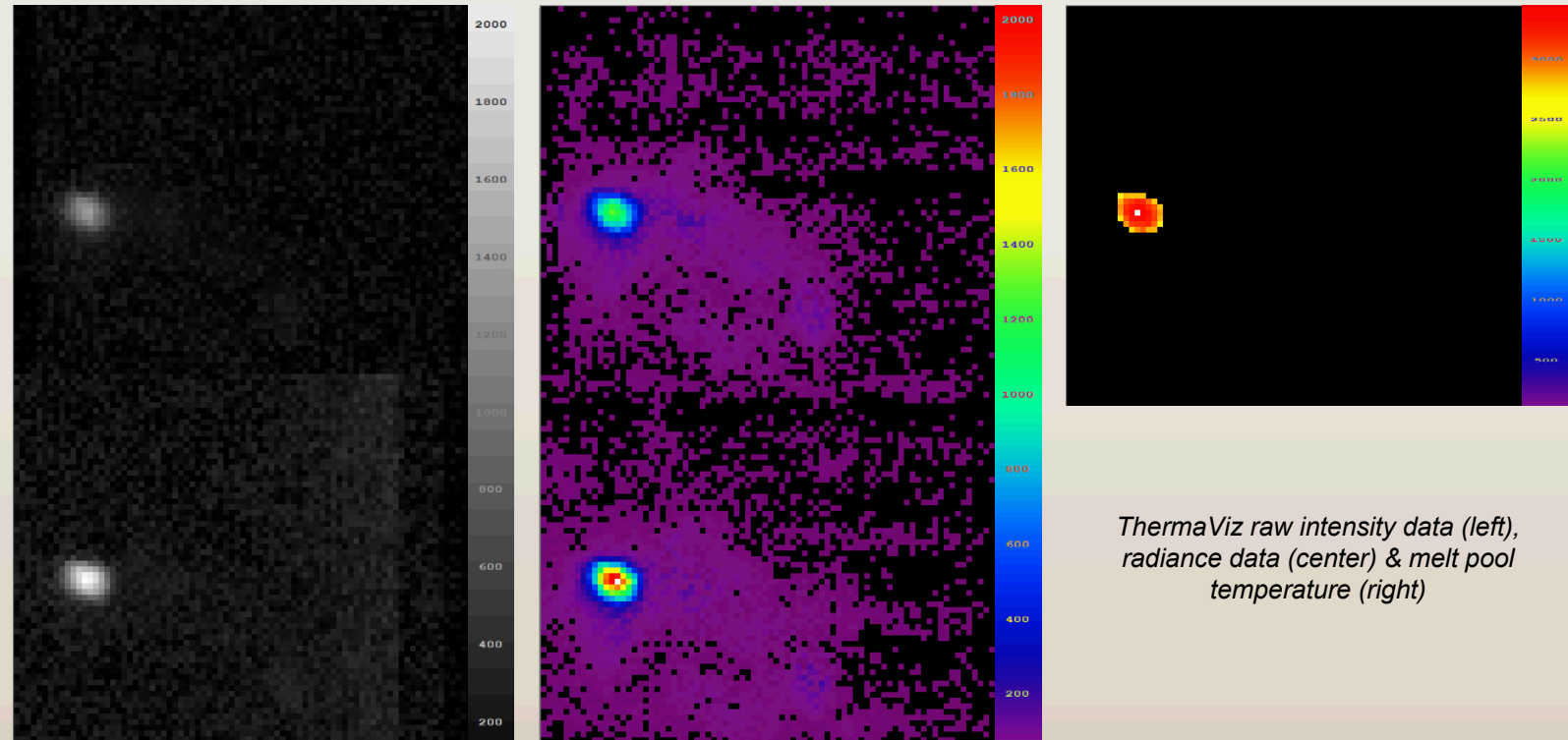


# Melt Pool Monitoring

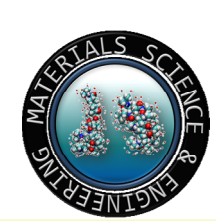
- Stratronics Therma-Viz two-color pyrometer
  - CMOS imagers,  $\sim 20\mu\text{m}/\text{pixel}$
  - 750 & 900nm filters (short & long)
  - $T_{\text{pixel}} \cong \text{func}(I_1 / I_2)$
- Fixed field, angled side viewing
  - FOV: 80 x 65 pixel (1.6 x 1.3 mm)
  - frame rate: 6-7kHz
  - exposure: 90 $\mu\text{sec}$
- Challenges
  - data rate
  - image resolution & registration
  - emissivity variation across melt pool



ThermaViz installed in the 3D Systems ProX 200

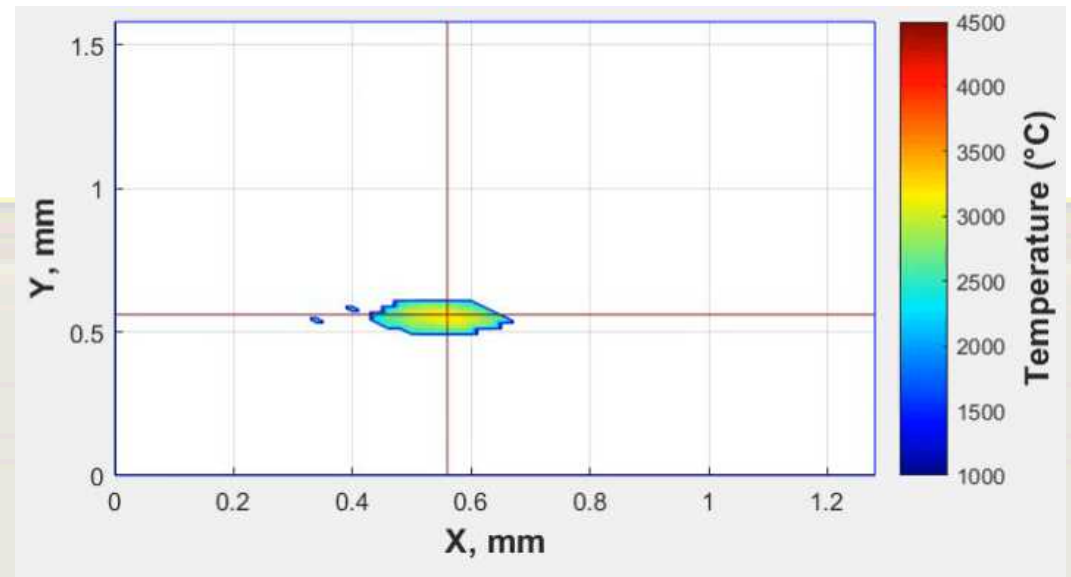


ThermaViz raw intensity data (left), radiance data (center) & melt pool temperature (right)

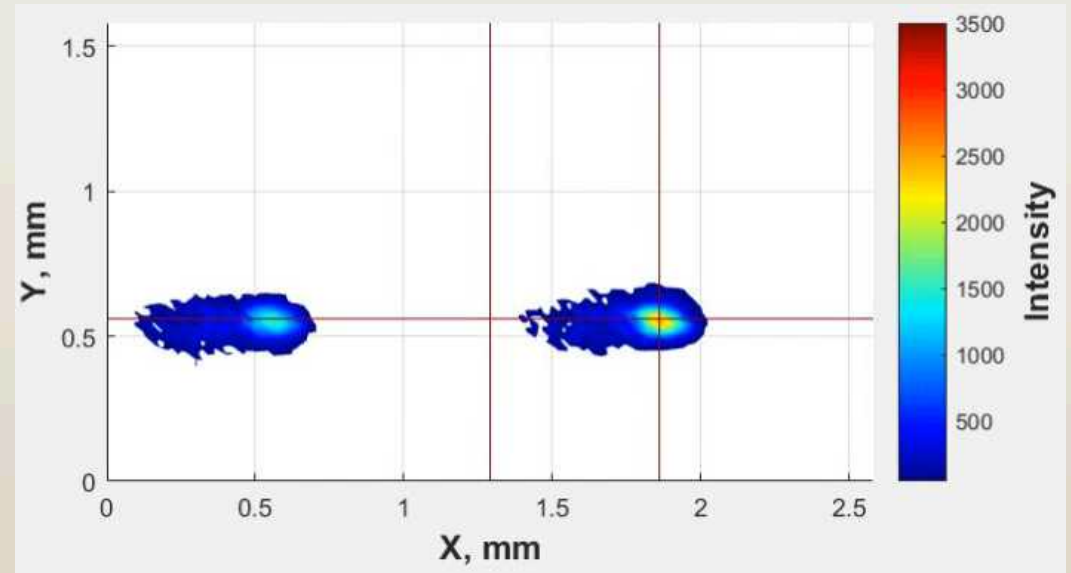


# Therma-Viz Data Analysis

- Registration tied to process layers
- Melt pool metrics
  - peak temperature, centroid location, area, length, width, kurtosis, skewness
- Two approaches
  - process experiments
    - Matlab, Stratonic CSVs, 10s-100s images
  - porosity column builds
    - Python scripts, Stratonic 'raw.viz' files, 100k images quickly (minutes)
    - compute pool properties using contour data



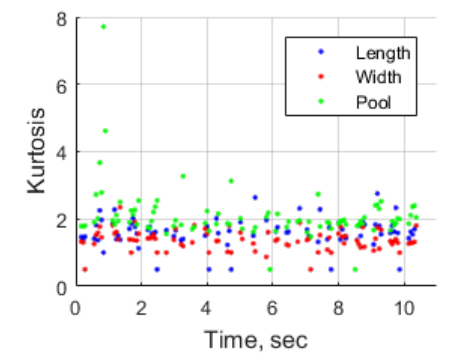
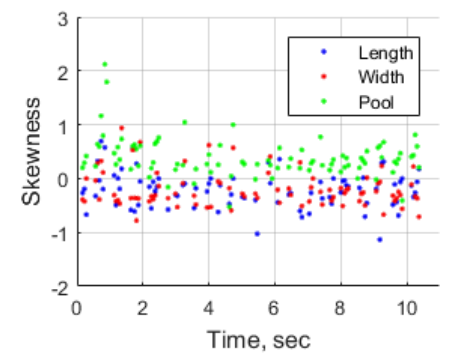
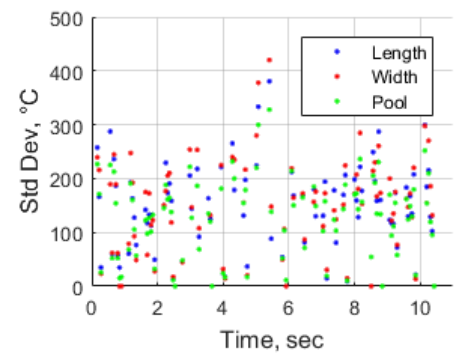
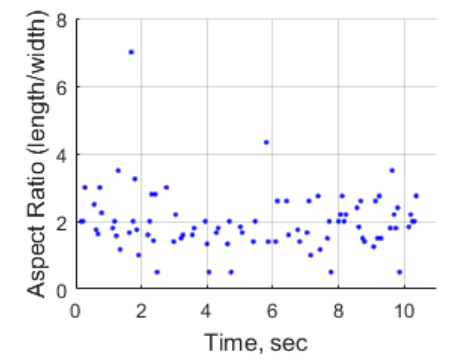
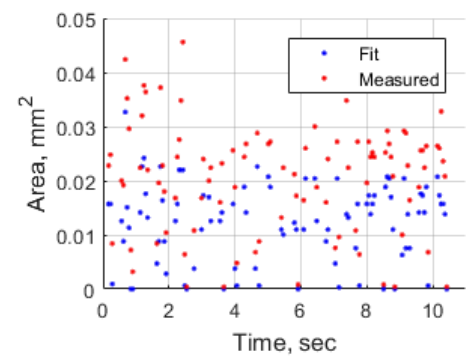
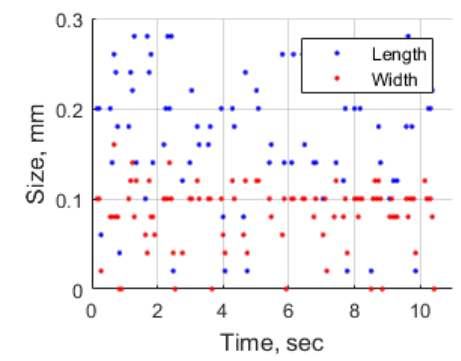
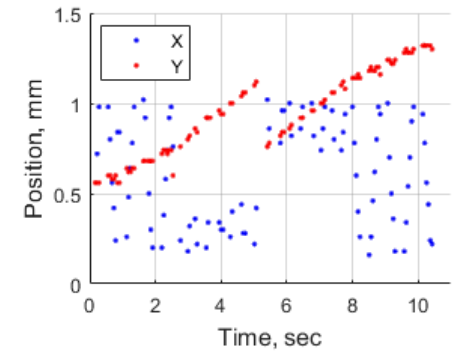
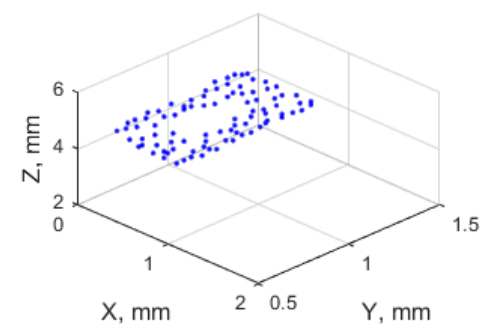
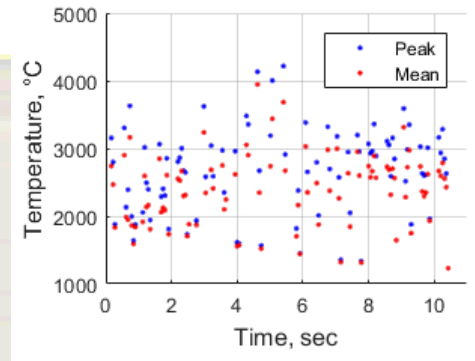
layer 161 melt pool temperature

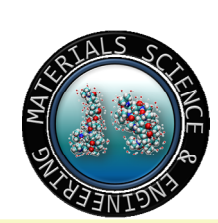


layer 161 melt pool raw intensity, short wavelength (left), long wavelength (right)

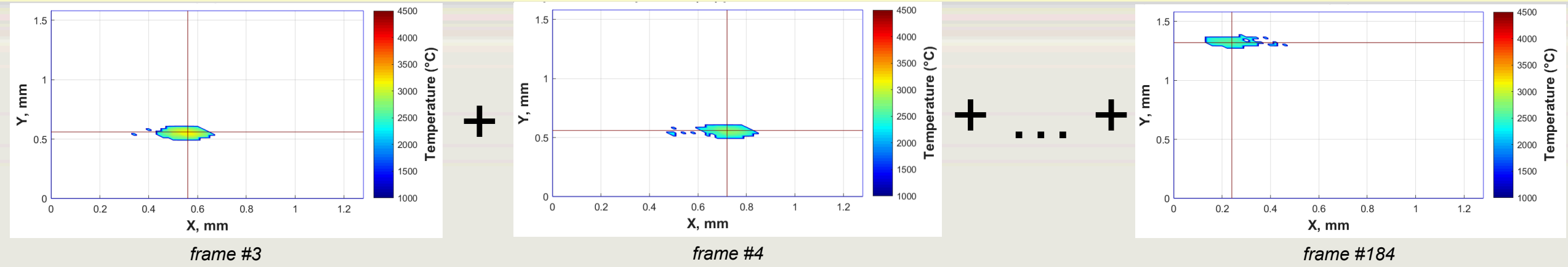


# Melt Pool Metrics

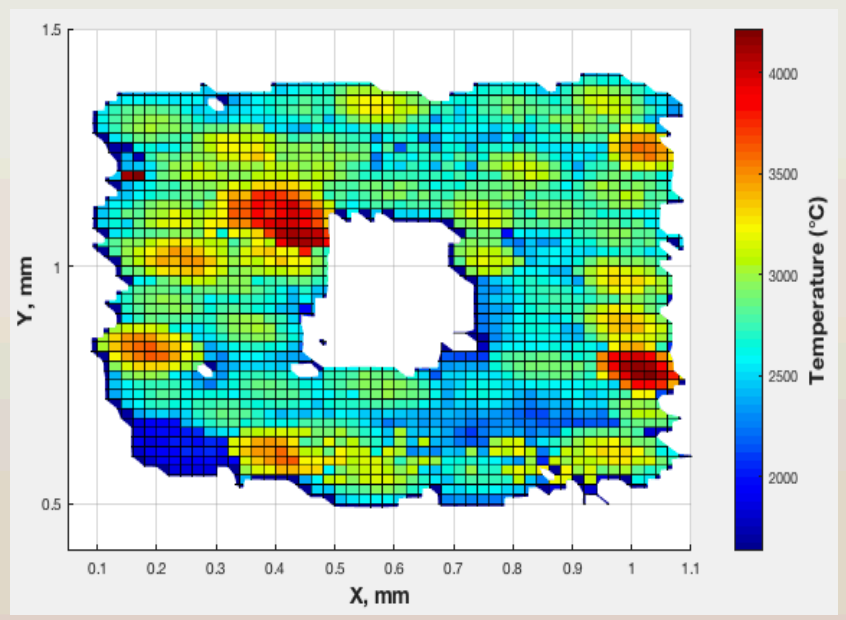




# Temperature Maps Developed Per Layer

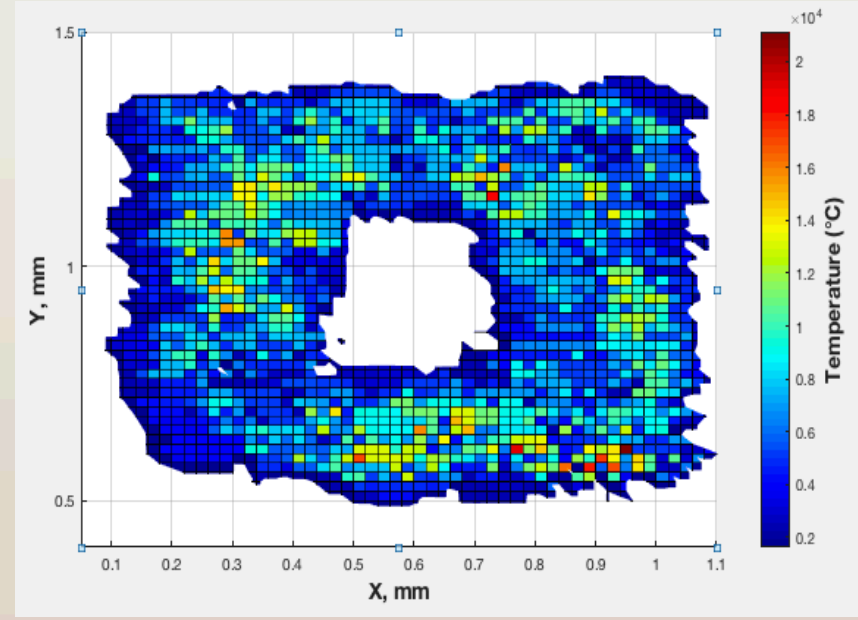


||



max temperature value @ each pixel across all frames

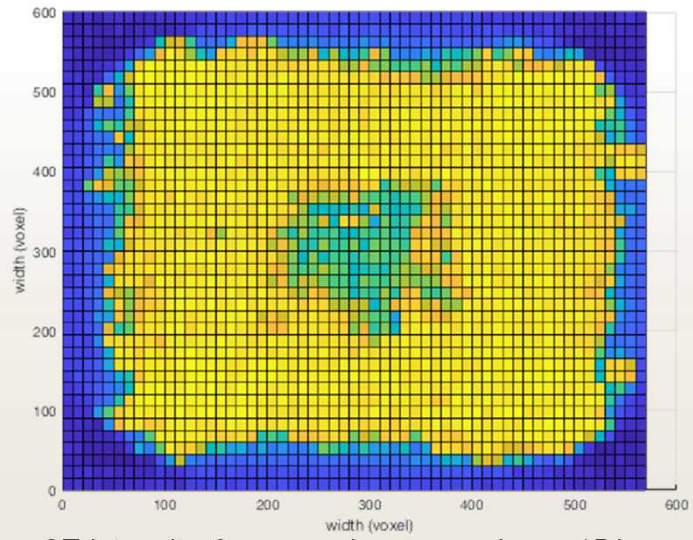
,



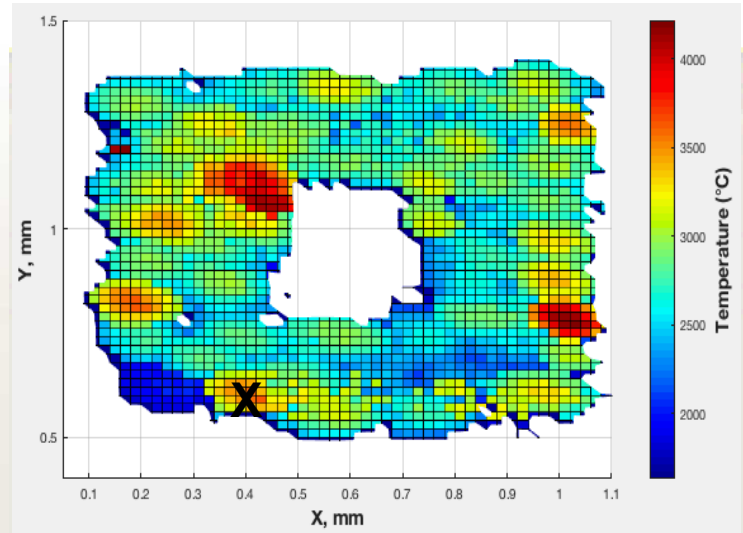
sum all temperature values @ each pixel across all frames



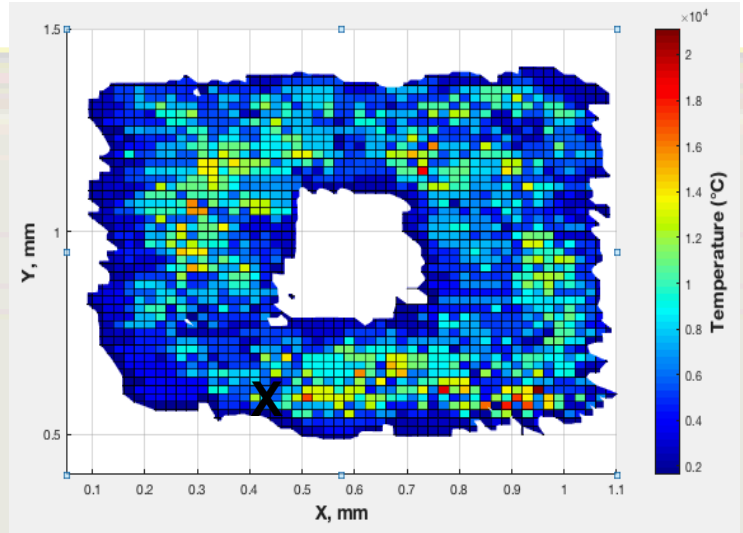
# Data Correlations – 300 $\mu$ m Pore, Layer 156



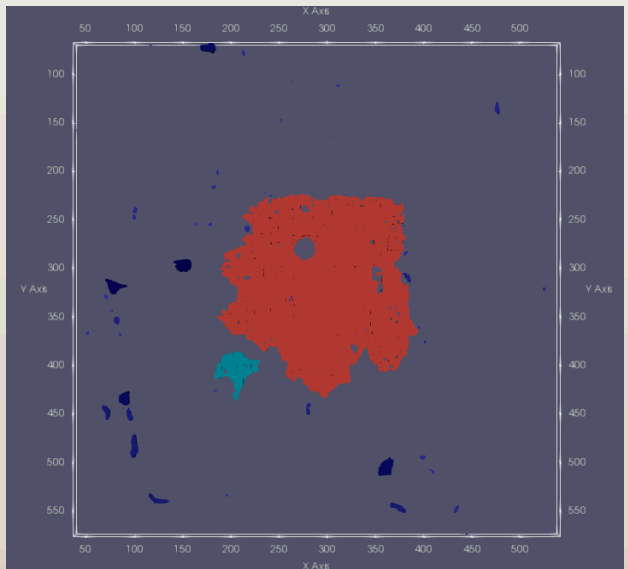
$\mu$ CT intensity, 2  $\mu$ m voxels averaged over 15 layers



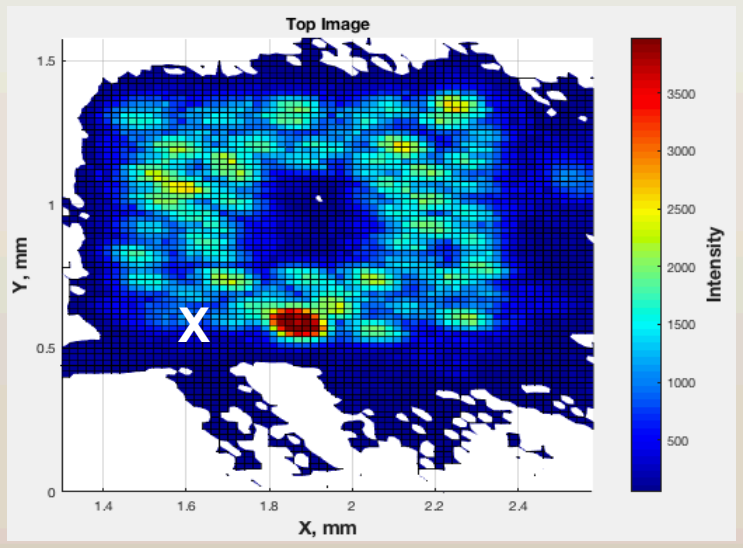
max temperature data



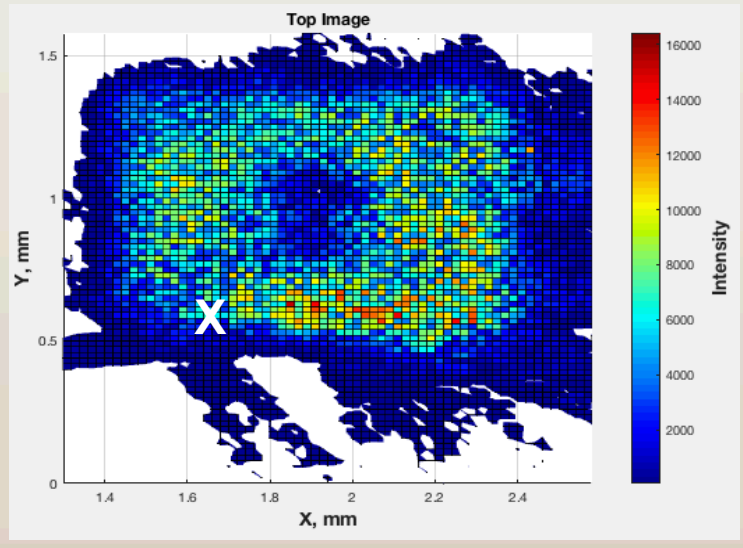
total temperature data



porosity



max intensity data, long wavelength



total intensity data, long wavelength



# Data Correlations – 30 $\mu$ m Pore, Layer ???

*$\mu$ CT intensity, 2  $\mu$ m voxels averaged over 15 layers*

X

*max temperature data*

X

*total temperature data*

X

*porosity*

*max intensity data, long wavelength*

*total intensity data, long wavelength*



# Data Correlations – Process Porosity

*$\mu$ CT intensity, 2  $\mu$ m voxels averaged over 15 layers*

*max temperature data*

*total temperature data*

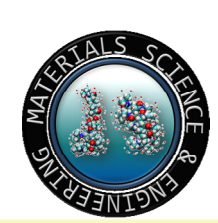
X

X

*porosity*

*max intensity data, long wavelength*

*total intensity data, long wavelength*



# Data Correlations – Overhang Data

*$\mu$ CT intensity, 2  $\mu$ m voxels averaged over 15 layers*

*max temperature data*

*total temperature data*

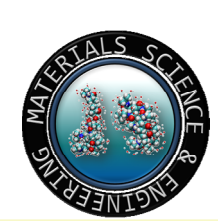
X

X

*porosity*

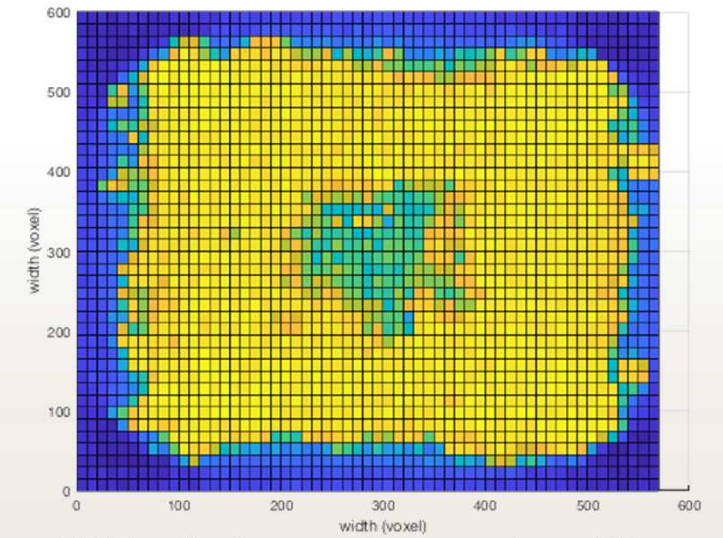
*max intensity data, long wavelength*

*total intensity data, long wavelength*

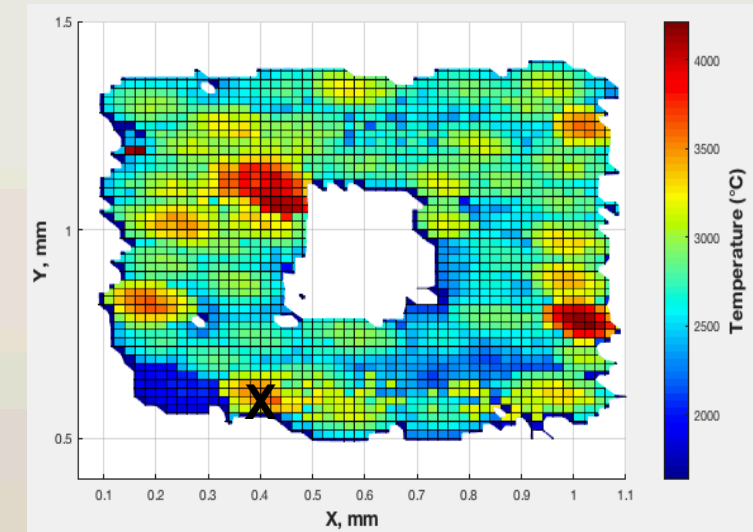


# Summary

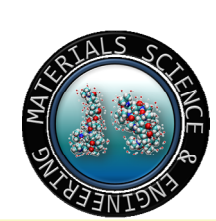
- Exploring two color pyrometry for porosity detection
  - absolute temperature accuracy is questionable
- Intentional porosity
  - observed in pyrometry data down to  $60\mu\text{m}$  size
  - $30\mu\text{m}$  pores  $\sim$  same scale as process porosity
- Process porosity
  - correlations less straightforward
  - additional analyses on-going
- Is lower resolution & slower data rates still useful?



*$\mu\text{CT}$  intensity,  $2\mu\text{m}$  voxels averaged over 15 layers*



*max temperature data*

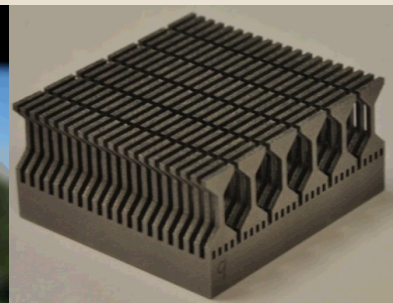
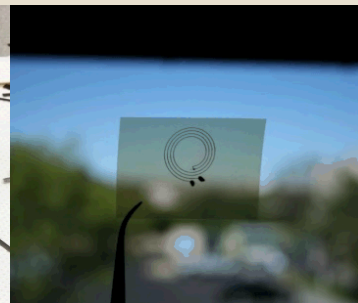
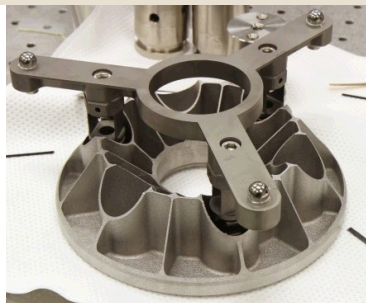
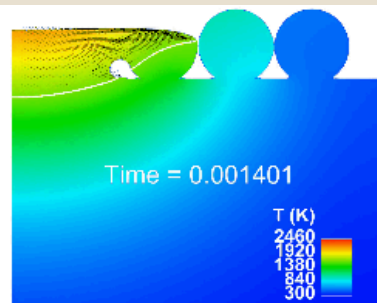
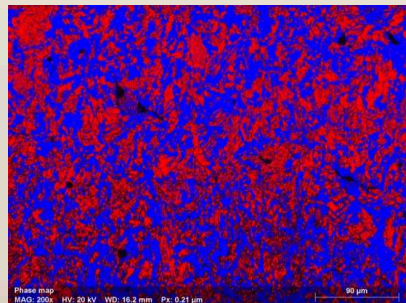


# QUESTIONS?

Bradley Jared, PhD

[bhjared@sandia.gov](mailto:bhjared@sandia.gov)

505-284-5890

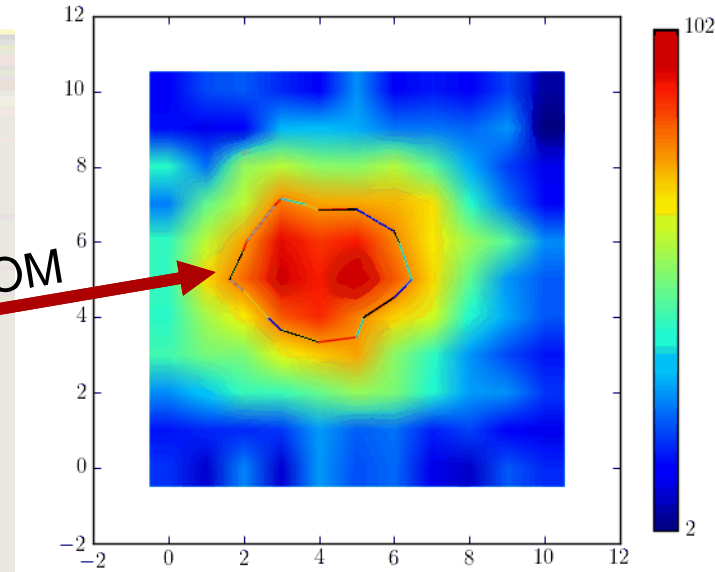
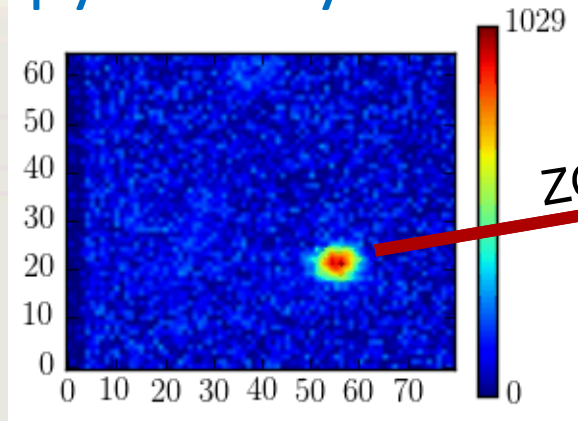




# Contours and pool area estimate

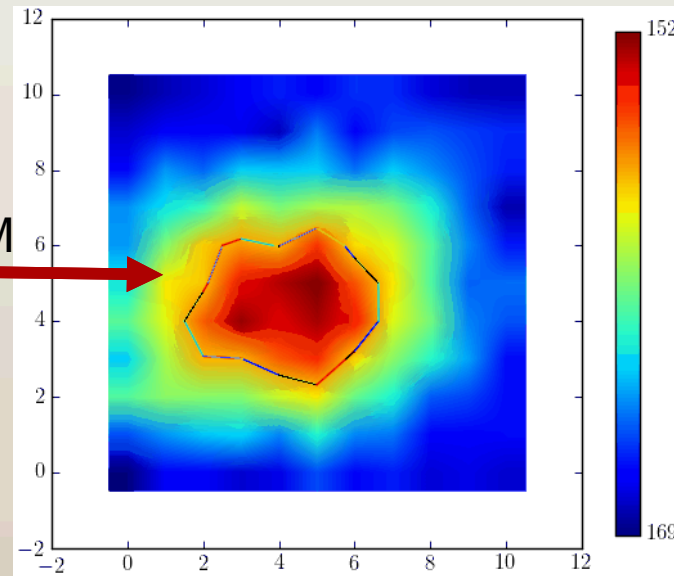
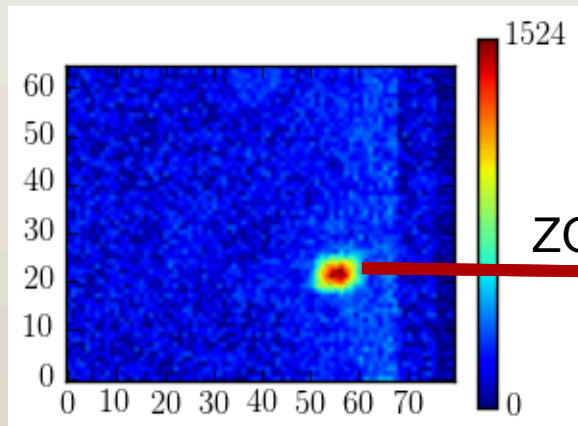
## Two-color

## pyrometry data



Pool area  
inside contour

Pool area=12.4  
(pixels squared)



Pool area=14.6  
(pixels squared)

Areas can be  
converted to units  
of area based  
upon camera  
resolution

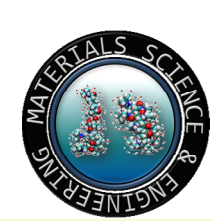
Data file

20170626/Layer 3-5/0095





- Slow velocity line scans
  - address limited frame rate
  - on-plate
    - better temperature values?
    - need to look at dendrite arm spacing to get cooling rates
- Melt pool response
  - shutter speed, sample rate
  - bead on plate, single powder layers
  - line & area scans
  - laser power, velocity, cross-feed



- To facilitate adoption in high consequence applications, fundamental questions regarding the intrinsic reliability of additive metals must be answered. Defect “signatures” are being investigated to provide a predictive framework for quantifying material performance distributions. Signatures for critical defects in stainless steel alloys will be discussed from multiple techniques that span in-situ process monitoring, post-process computed tomography, metallography and tensile testing. Process signatures will be of particular focus and will address thermal, optical and acoustic domains with the intent to quantify melt pool dynamics and defect formation in-situ.