SAND2022-7683C

30TH

RESEARCH SYMPOSIUM

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Hilton St. Louis Frontenac

St. Louis, Missouri, USA

ASNT | EVENTS.

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Characterization of Additively Manufactured Circular Disks Using Traditional Computed Tomography Volume Segmentation and Machine Learning Algorithms

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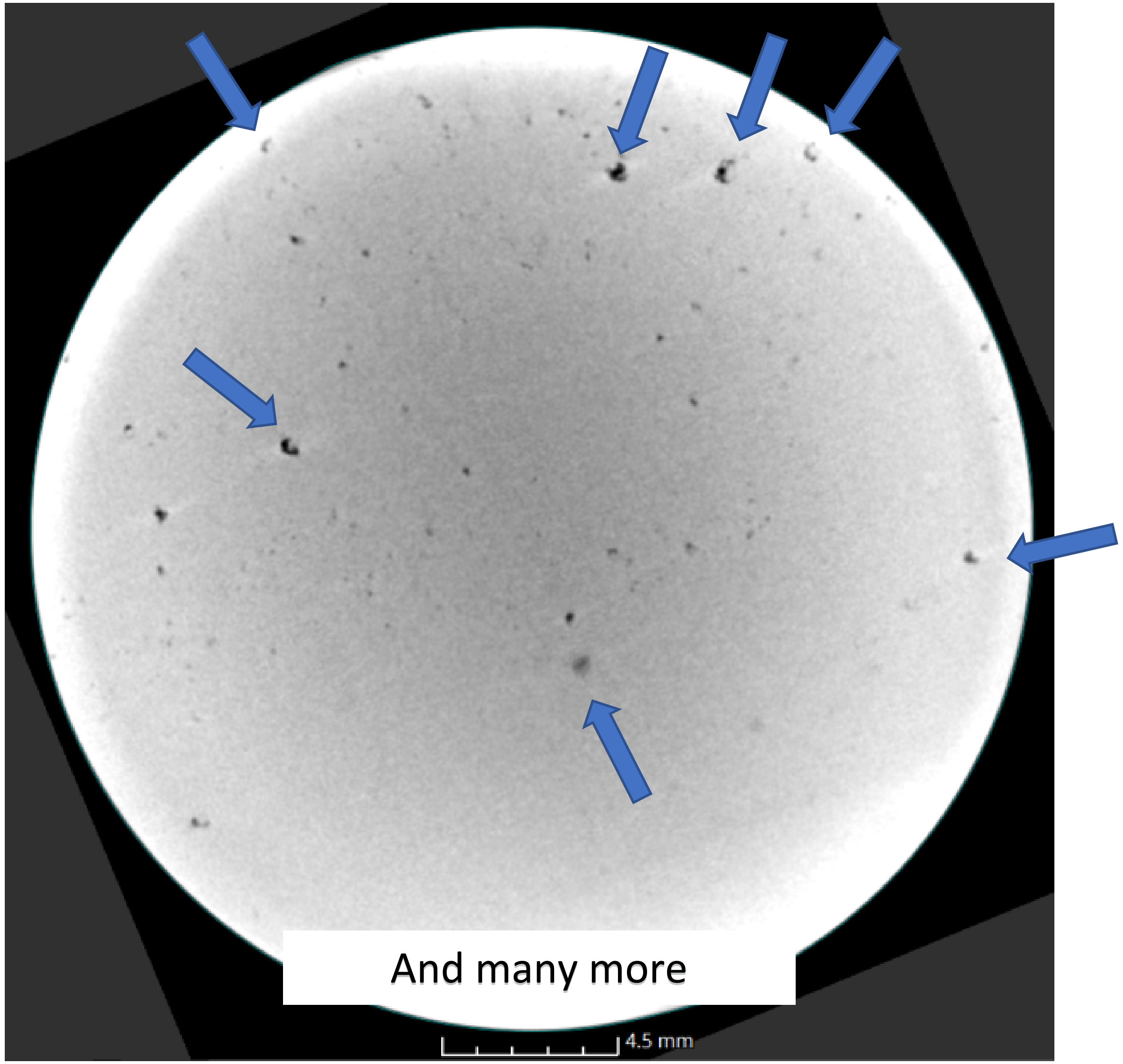
Purpose:

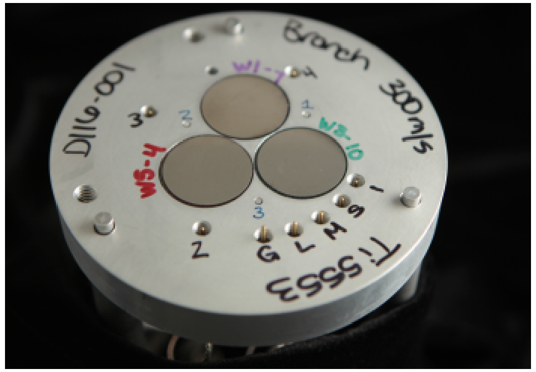
- Accurate and precise identification of defects in AM components
- Assessing the resolvability of defects with X-ray computed tomography vs serial sectioning
- Identifying the role of machine learning in defect identification
- Characterizing how defects effect the formation of spall cavitation

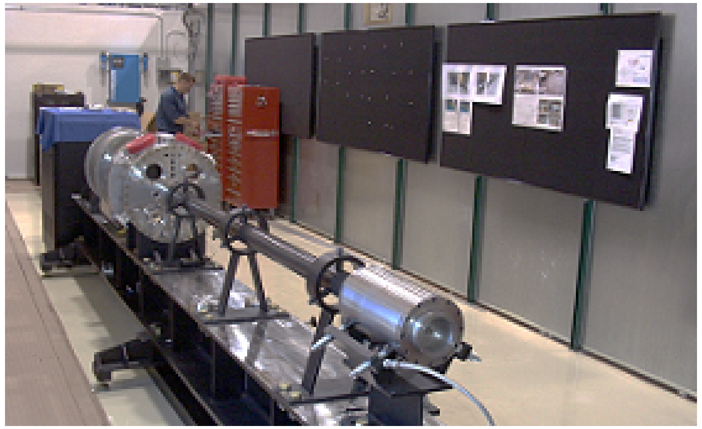


AM Sample Production and Experimental Setup

- Fabrication:
  - Material: Ti-5Al-5V-5Mo-3Cr
    - Ti-5553
  - System: Renishaw AM250 LPBF
  - Beam Type: Yb-Fiber power modulate
  - Beam Power: 200 W - 1070 nm
  - Pattern:
    - Layer-to-layer rotation: 67^{o}
    - Focal spot: 70 µm
    - Slice thickness: 60 µm

- Testing:
  - Test Performed: High-velocity impact loading
  - System: Gas Gun
  - Impact Velocity: 300 m/s (671 mph)

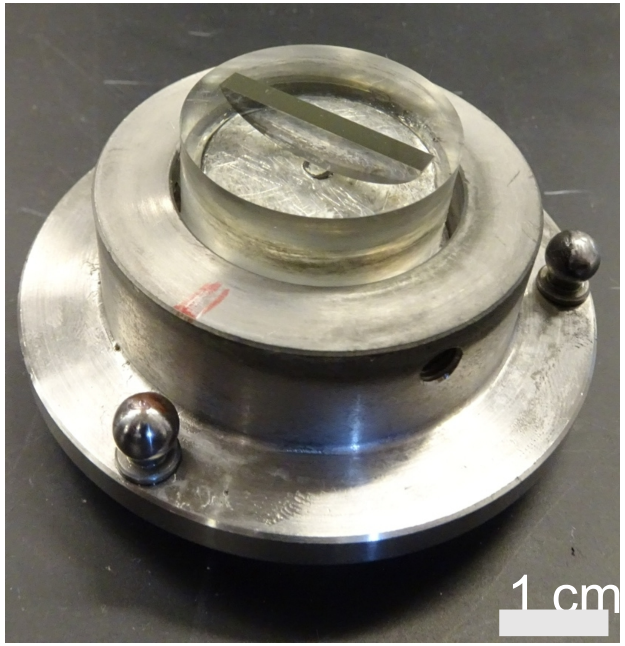


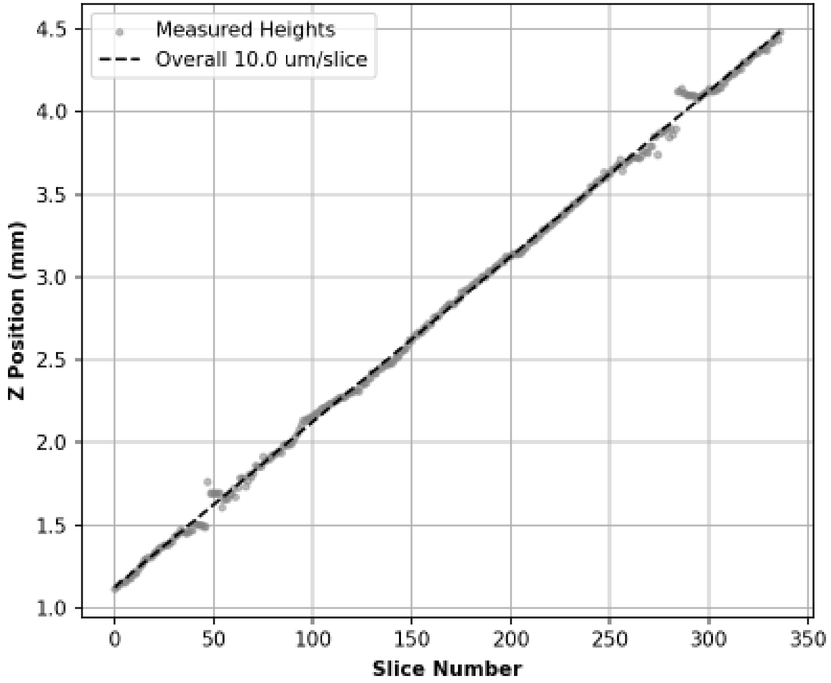


Dynamic Integrated Compression Experimental Facility at SNL

Serial Sectioning Technique:

- Serial Sectioning:
  - System: Robomet automatic sectioning
  - Resolution:
    - 10 µm a slice
    - 1.08 µm pixels
  - Time:
    - 20 slices an hour
    - ~ 50 hours total





Segmentation and Porosity Analysis:

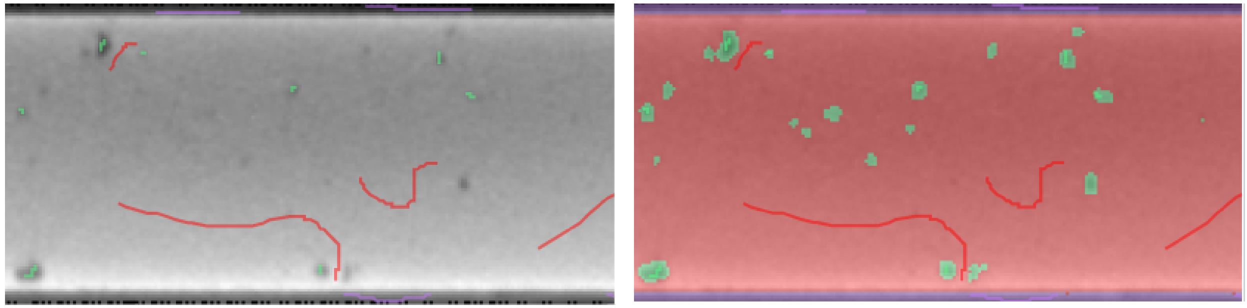
- Porosity Analysis:
  - Data Type: 16 bit voxel data
  - Software: Volume Graphics – VGStudioMax 3.5
  - Parameters chosen to optimize porosity assessment (iterative)

- Histogram of gray values:
  - Material peak (M)
  - Background peak (B)
  - Standard deviation (σ)

- Thresholding:
  - Interpolation based: B + (M-B)*C1
  - Interpolation factor (C1)
    - XCT: 0.95 SS: 0.64
- VGDefX:
  - Standard deviation based: M + σ*C2
  - Deviation factor (C2)
    - XCT: -0.5 SS: -2.5
- VGEasyPore:
  - Contrast based in local window (10 vx width)
  - Absolute contrast: gray value difference
    - XCT: 1000   SS: 34.8
  - Relative contrast: % of gray value difference
    - XCT: 6% SS: 10%

Machine Learning on CT Image Stacks

- Porosity Analysis:
  - Data Type: 16 bit voxel data
  - Software: ImageJ -> Trainable WEKA Segmentation 3D



- WEKA:
  - Machine learning segmentation
  - Generates additional feature volumes from input volume
  - User marks examples of each class/label
  - Random forest training for deterministic class assignment based from data in the volumes

Machine Learning Inputs

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- WEKA Extended:
  - Marks are made over regions of gray-scale slice data and then assigned a label
    - User intuition and perception is translated into training data
    - Intuitive assignment and iteration improve AI identification
  - Features are generated to expand the input data
    - Features used: Gaussian blur, difference of Gaussians, derivatives, Laplacian, Hessian, median, and variance
    - Six kernel sizes used ranging from 1 to 8 voxels in width
  - Continuity is maintained by training on all the disk volumes simultaneously
    - Volumes are concatenated along their 3rd dimension
    - Training is iterated until prediction is optimal for all disks

Comparison of Porosity Identification:

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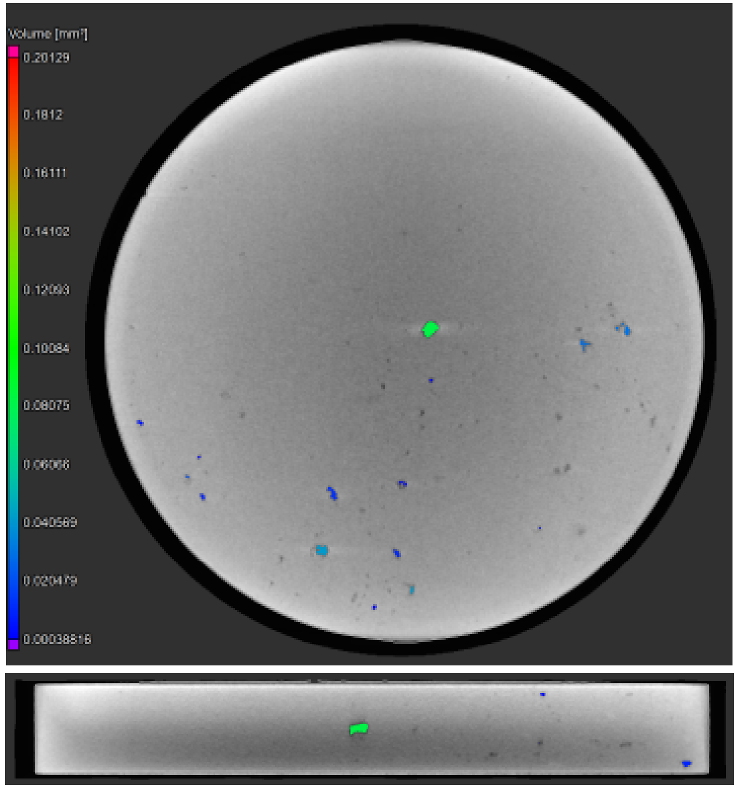
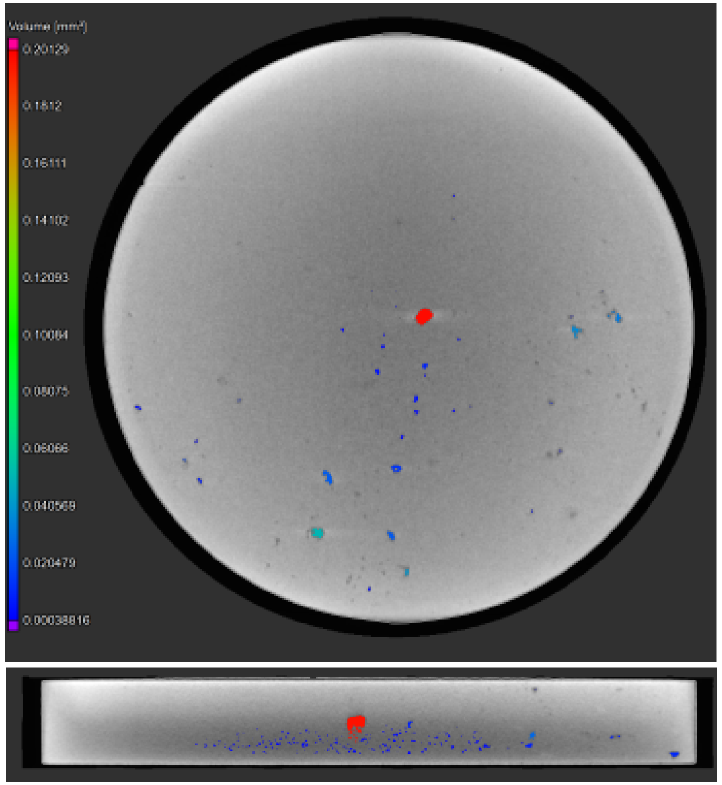
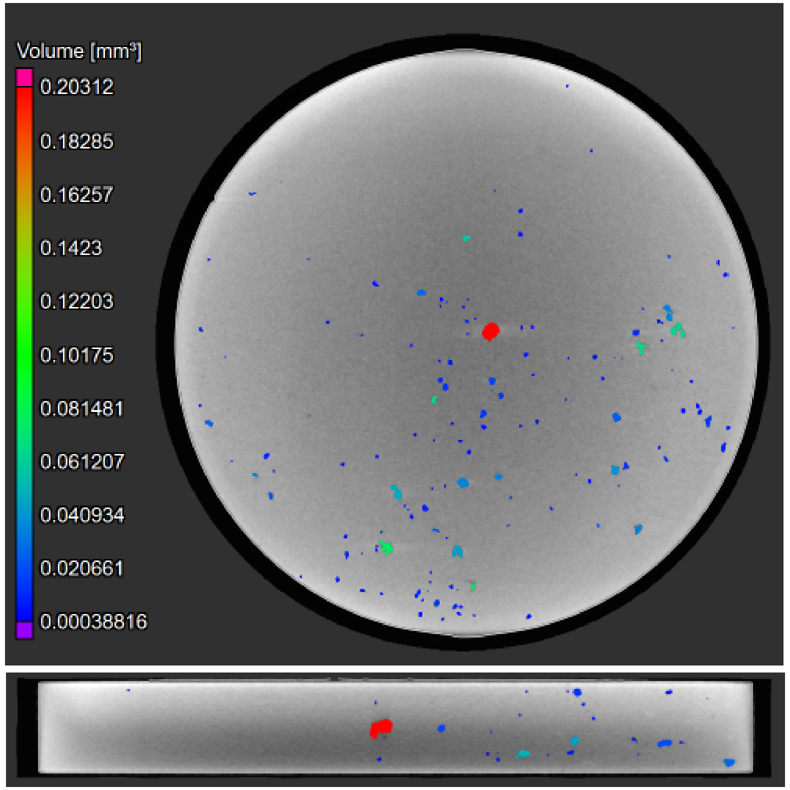
VG-Easy Pore (Local Contrast)



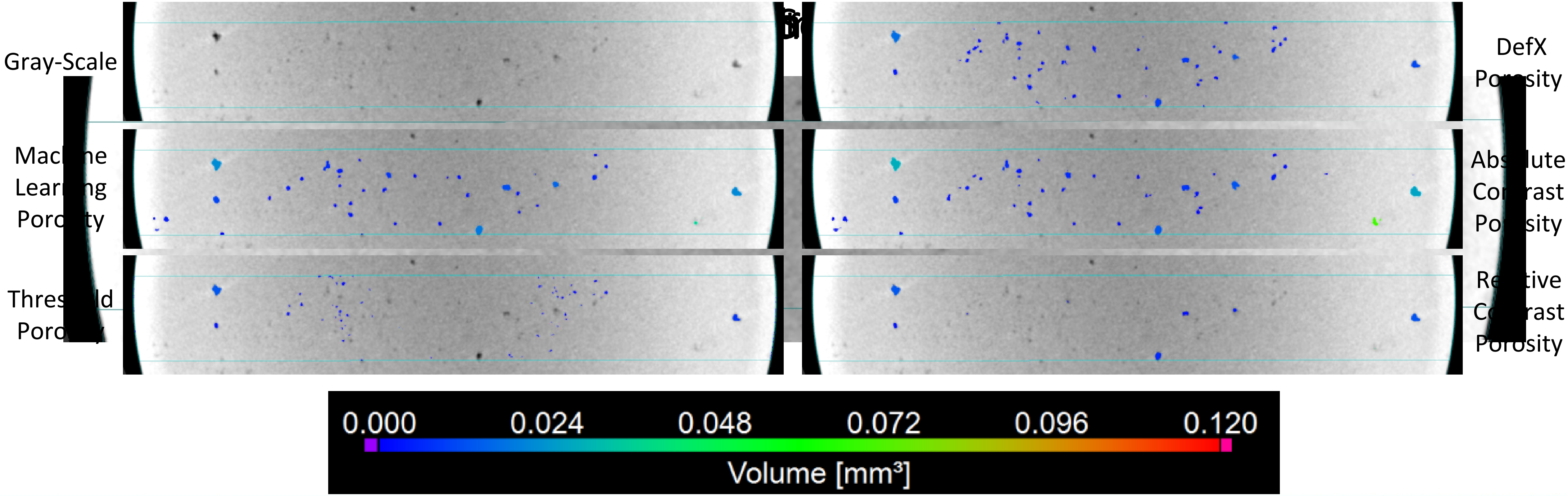
VGDefX (Deviation Threshold)



WEKA (User input + AI)



Segmented Porosity Results:



Serial Sectioning Segmented Porosity Results:

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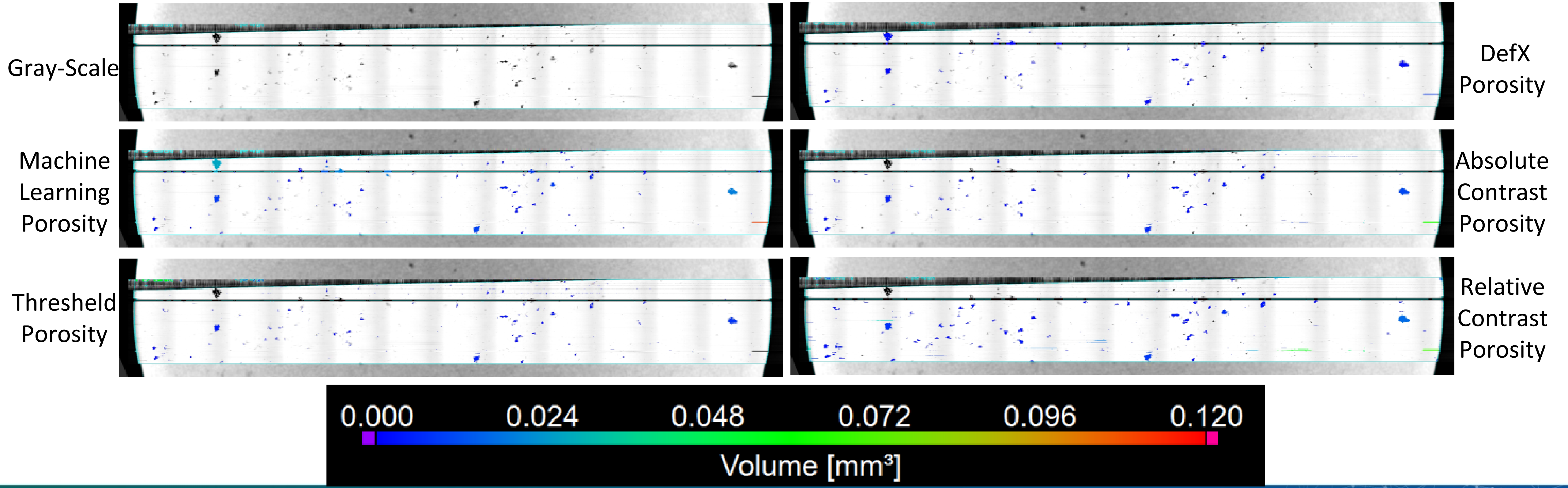
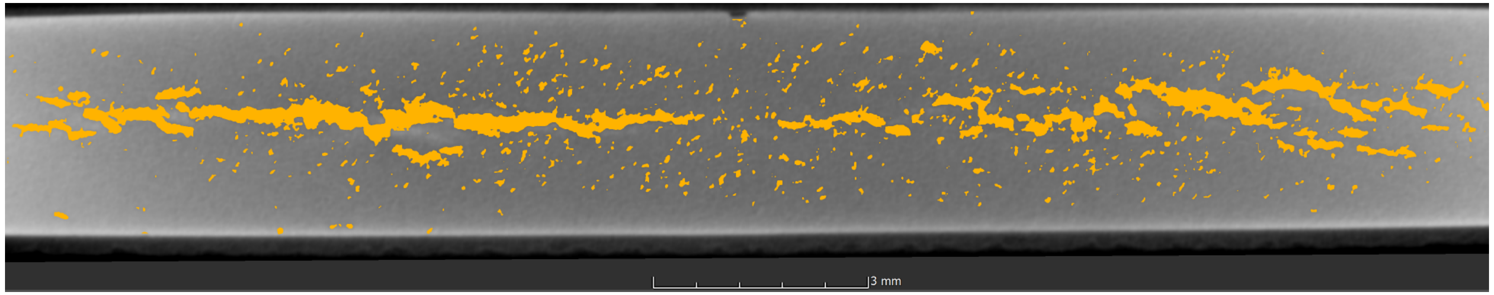


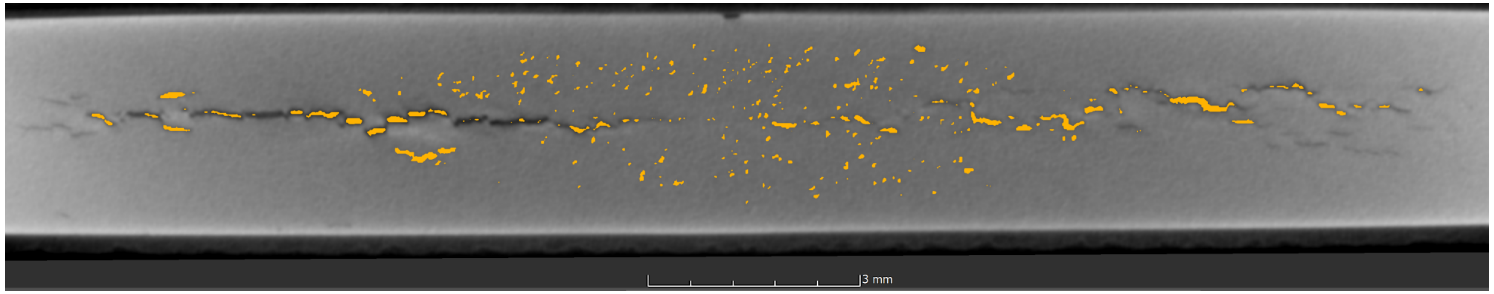
Spall Plane Results:

- XCT Segmented Spall:
  - Porosity identification techniques
  - Contrast changes affect identification

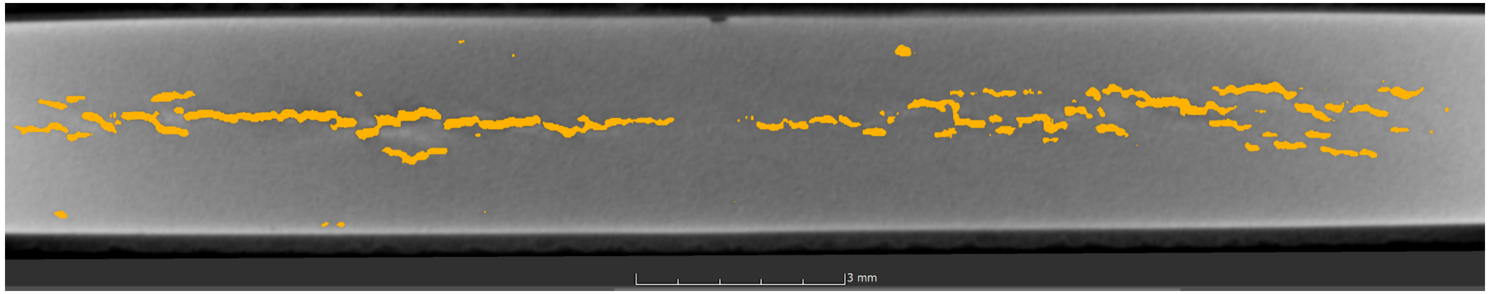
Local Contrast



Deviation



Machine Learning



Isometric View of Spall Planes:

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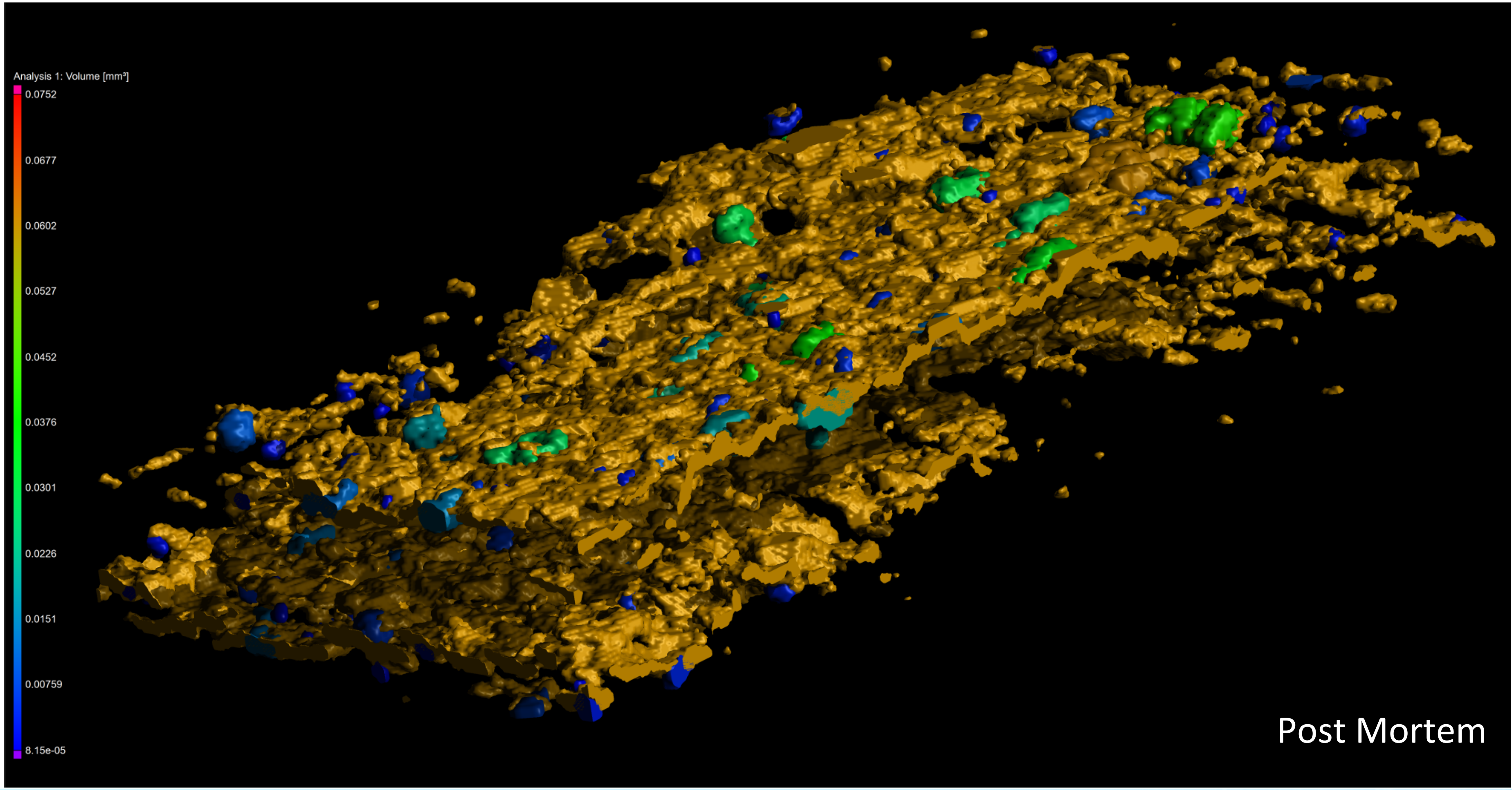
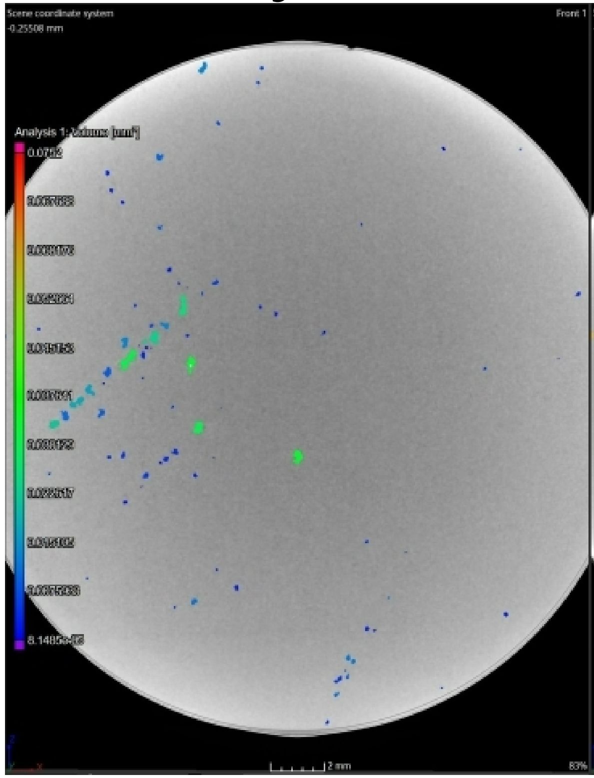
- XCT Segmented Spall:
  - Comparison of Porosity with spall plane formation

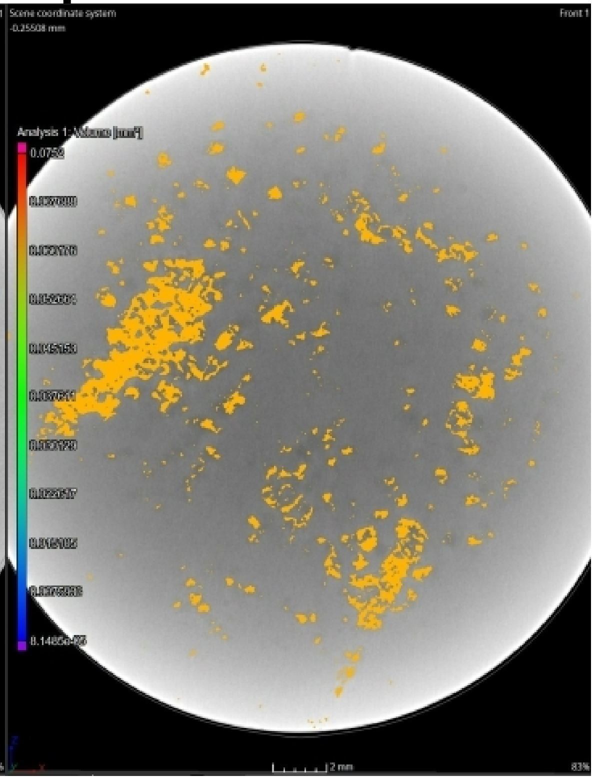


Comparing Porosity and Spall Cavitation:

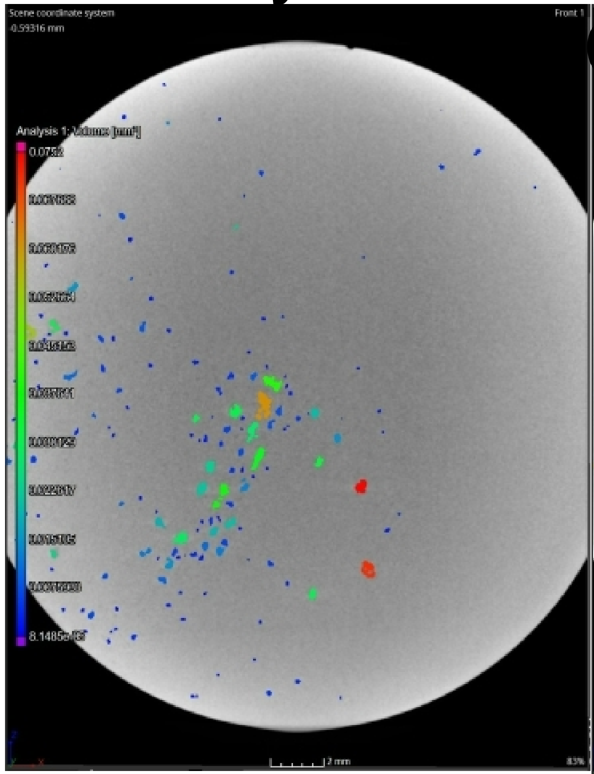
Porosity



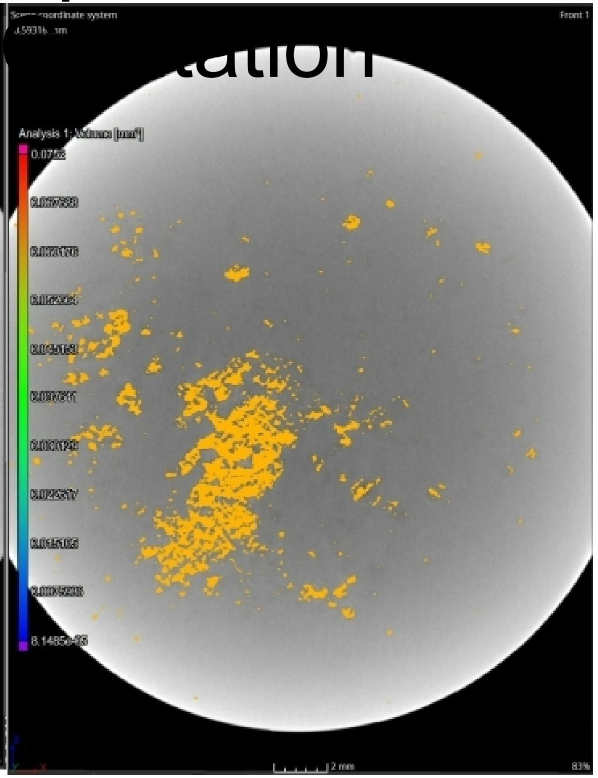
Spall



Porosity



Spall



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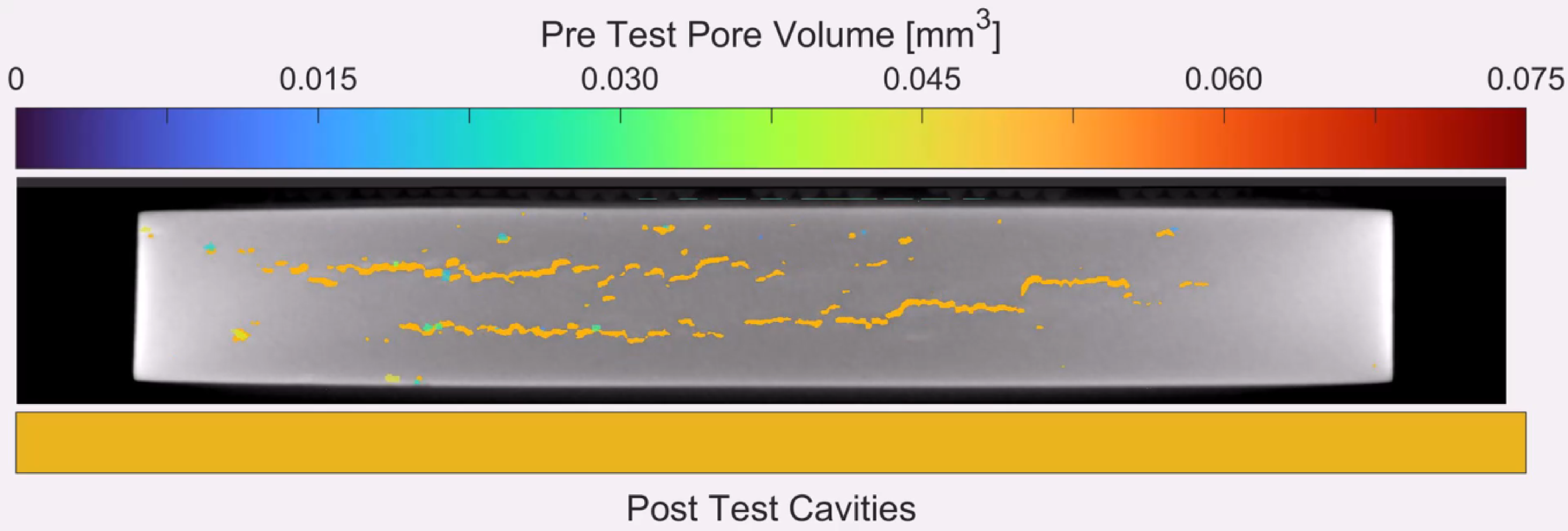
Pre and Post Impact Comparison

- Comparing Porosity and Spall Cavitation:



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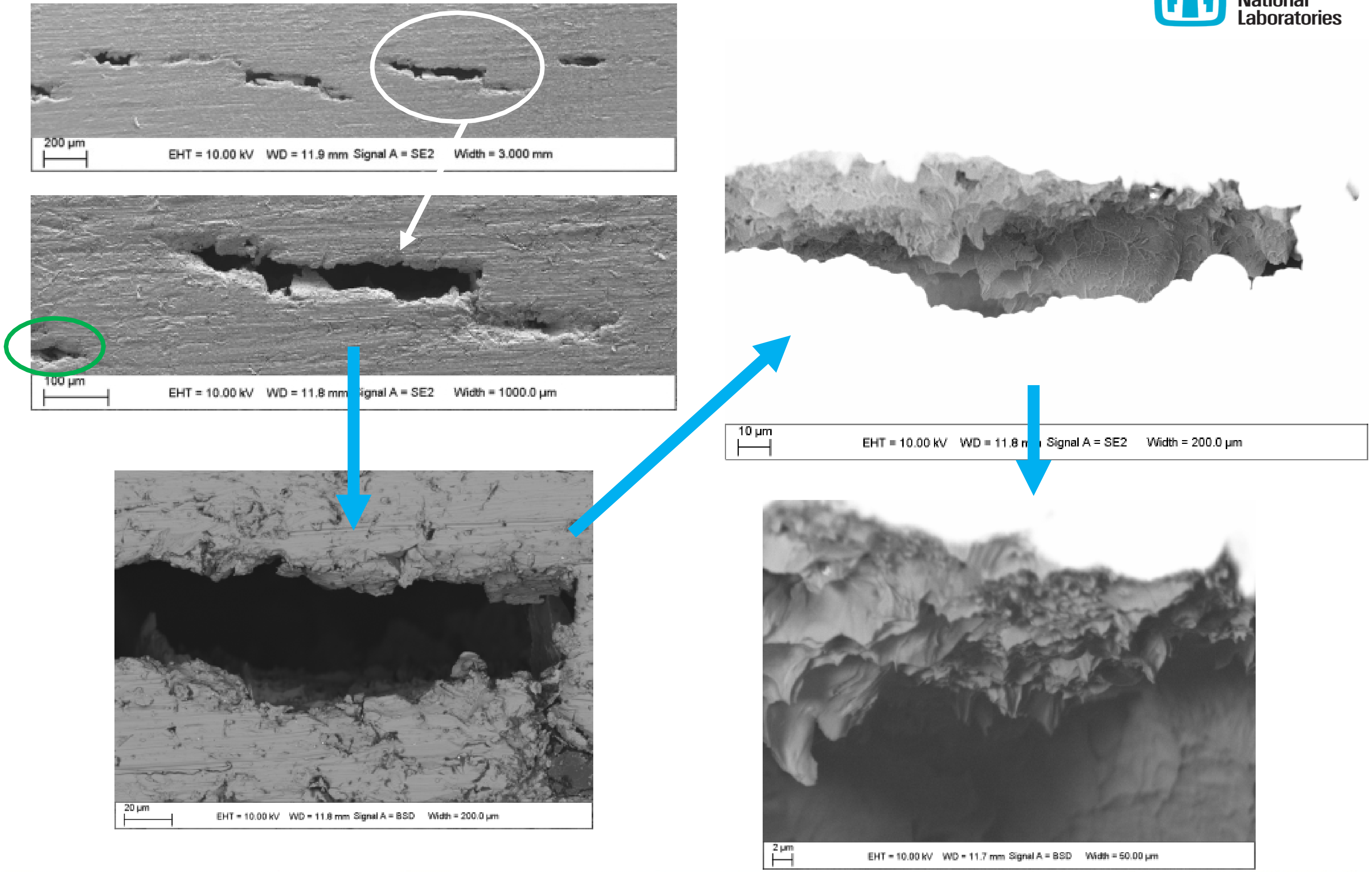
Results:

- SEM Spall:
  - Cross section of spall plane
  - Tensile fracture
  - Interaction with porosity



Porosity Detection (Conventional versus ML):

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- Comparison of porosity with different porosity identification techniques:
  - Porosity identification is a function of signal to noise ratio (SNR)
  - Additional errors may occur due to changing contrast in the reconstruction

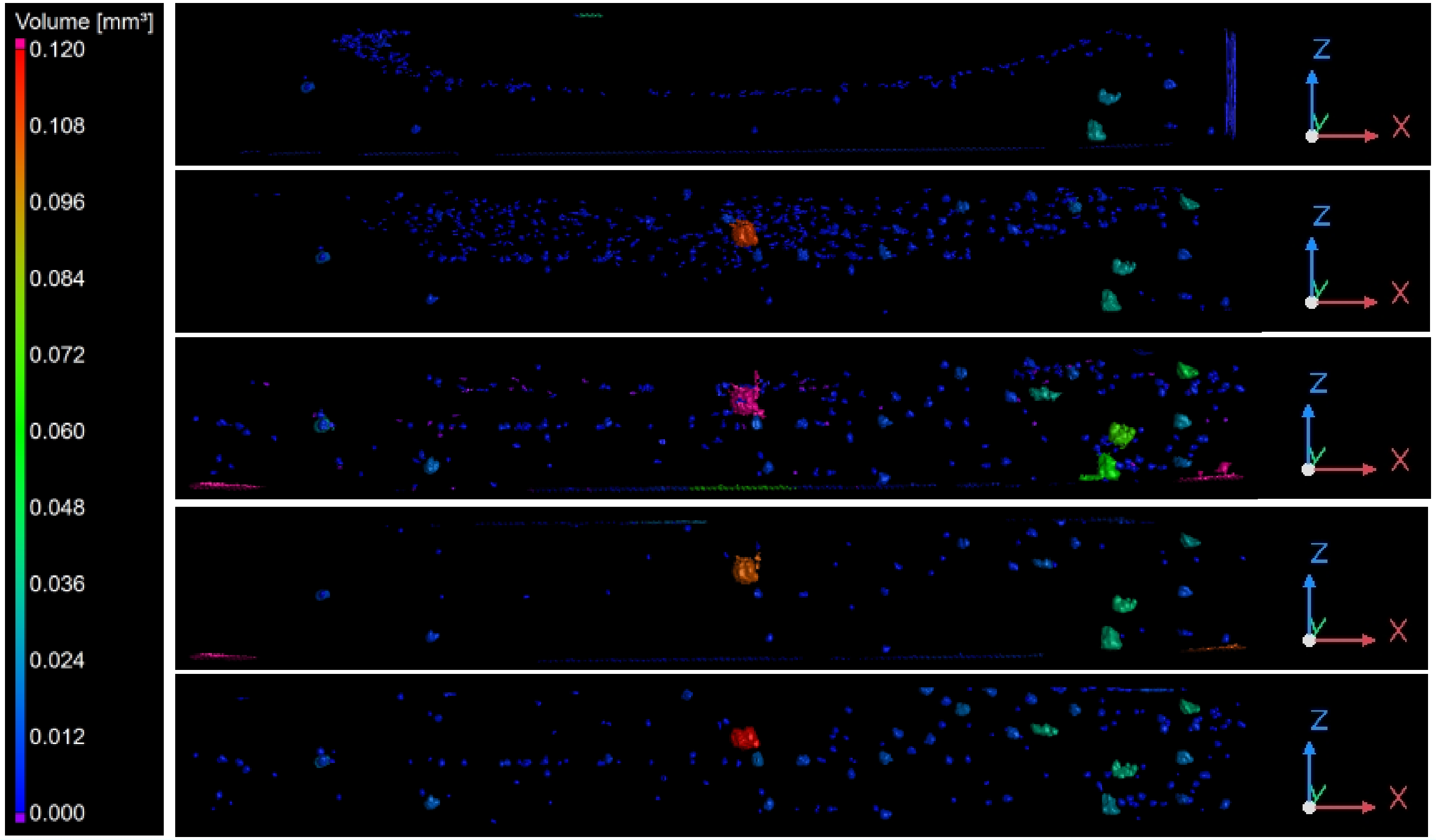
XCT – ISO Thresholding

XCT – Deviation Threshold

XCT – Global Contrast

XCT – Local Contrast

XCT – Machine Learning



Data Comparison for Scoring Indications:

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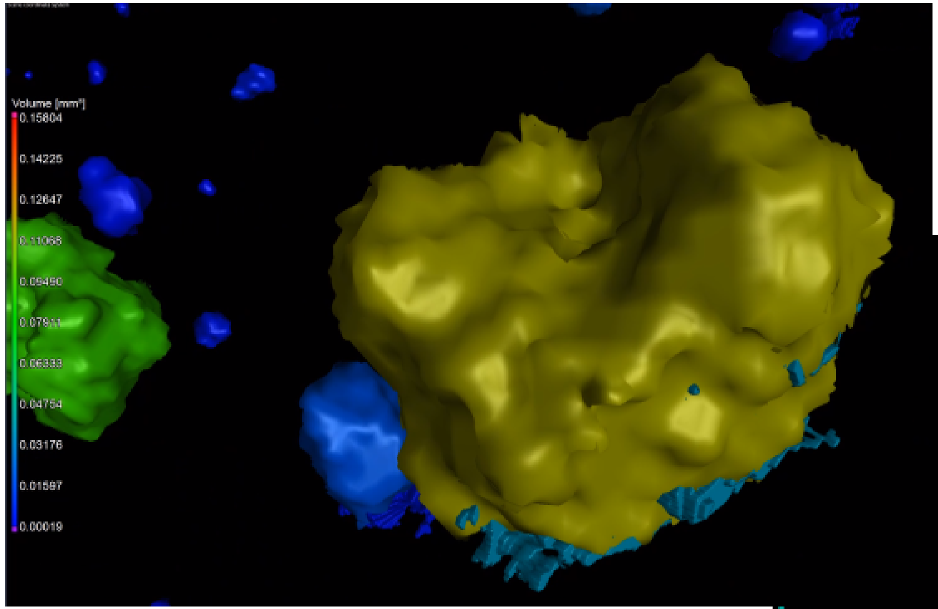
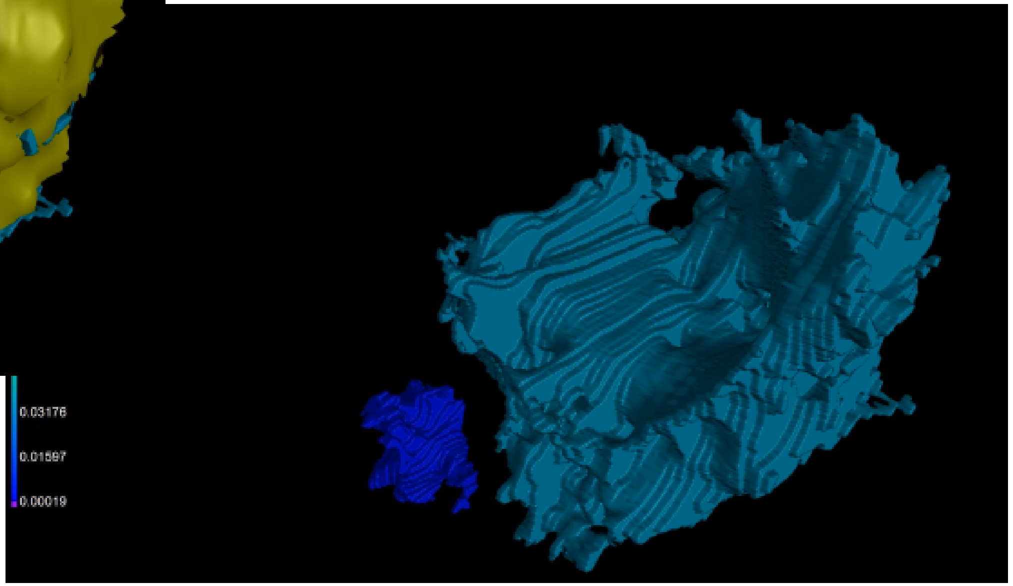
- Comparison of porosity between serial sectioning and XCT techniques:
  - SS vs XCT
    - Differences in resolution
    - Congruous reconstruction (XCT) layer-wise reconstruction



XCT and SS

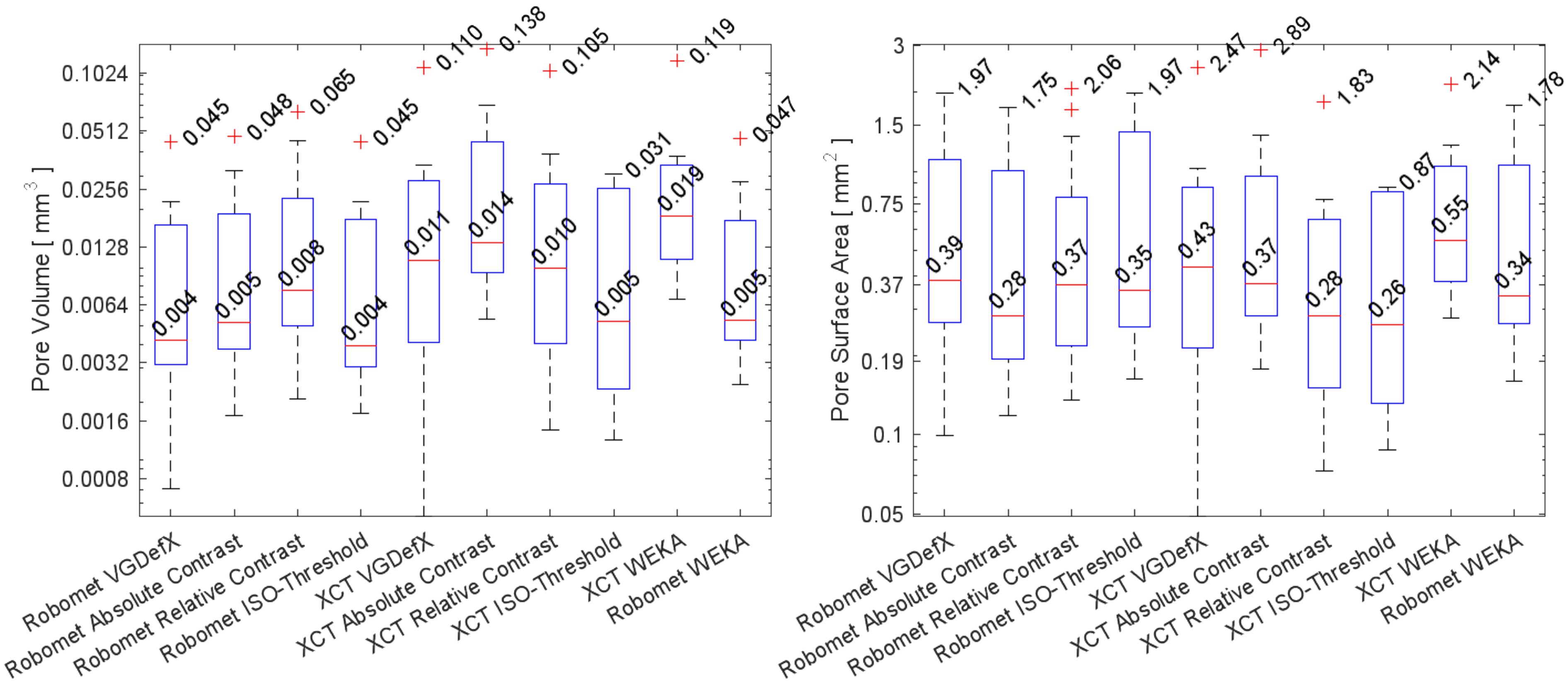
The lines within the image are 10 µm cut lines



SS only

Statistical Distribution of Detected Pores:

- Comparison of XCT and serial sectioning identification techniques:
  - Variation in pore volume and surface area between XCT and SS is on par with the order of magnitude difference in resolution

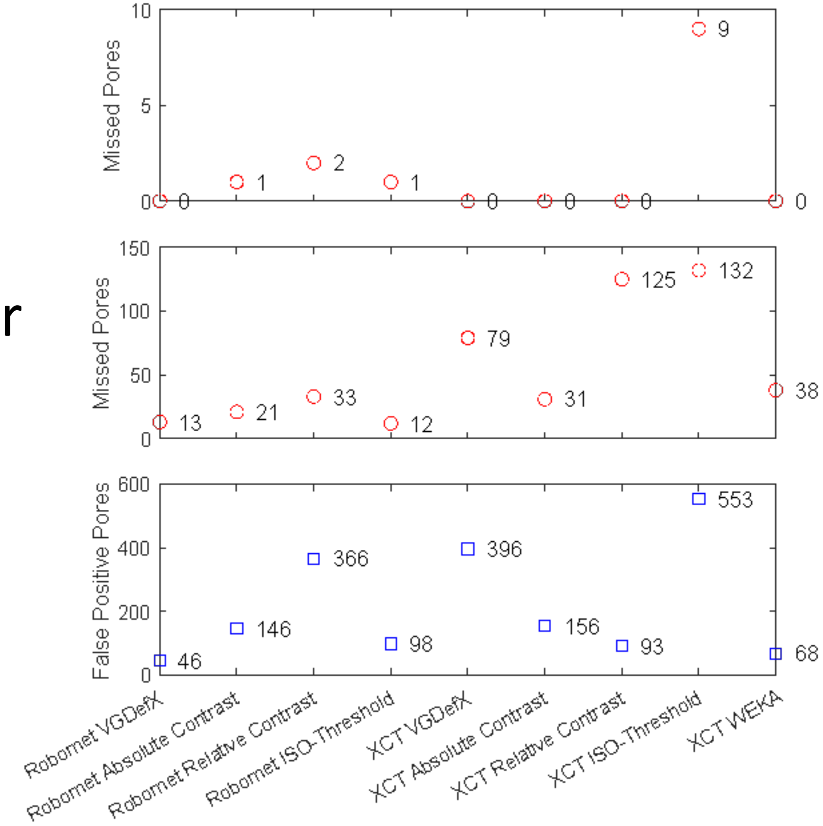


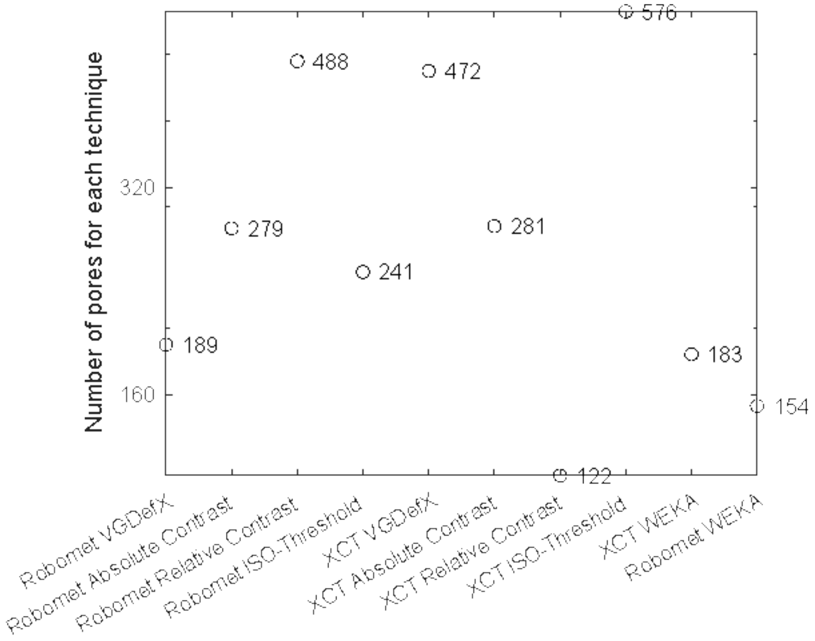
Statistical Distribution of Largest Pores:

- Comparison of XCT and SS identification techniques:

Comparing only the top 15 largest pores

Comparing all pores greater than 0.0004 mm^3





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Conclusions:

- Commercial porosity identification techniques are enhanced by ML
- ML performed better in terms of small pore identification and robustness to false positive identification
- ML is extremely computationally expensive compared to commercial techniques (days of analysis and 100s GBs of RAM)
- XCT results faired well against SS
  - Major porosity identified by both
  - Discrepancies with small pores near the detectability limit of XCT
  - XCT is faster
  - Both techniques produce artifacts
- SEM confirmed tensile fracture and interaction with porosity

Shock Compression Background

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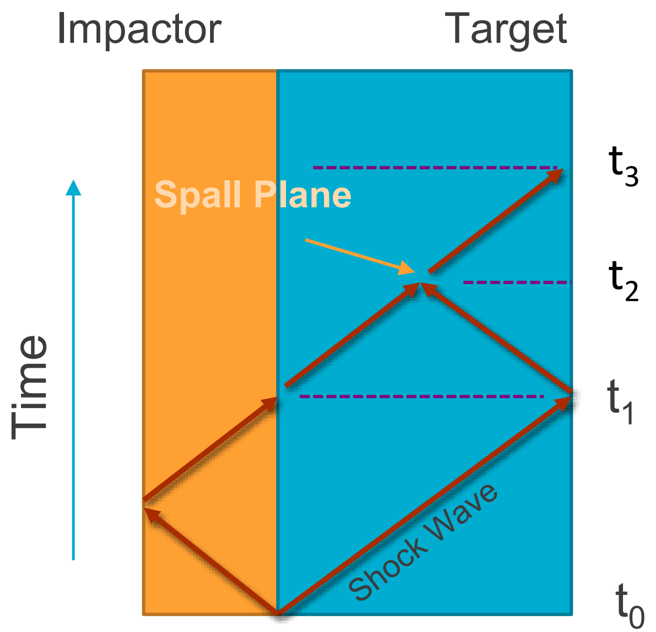
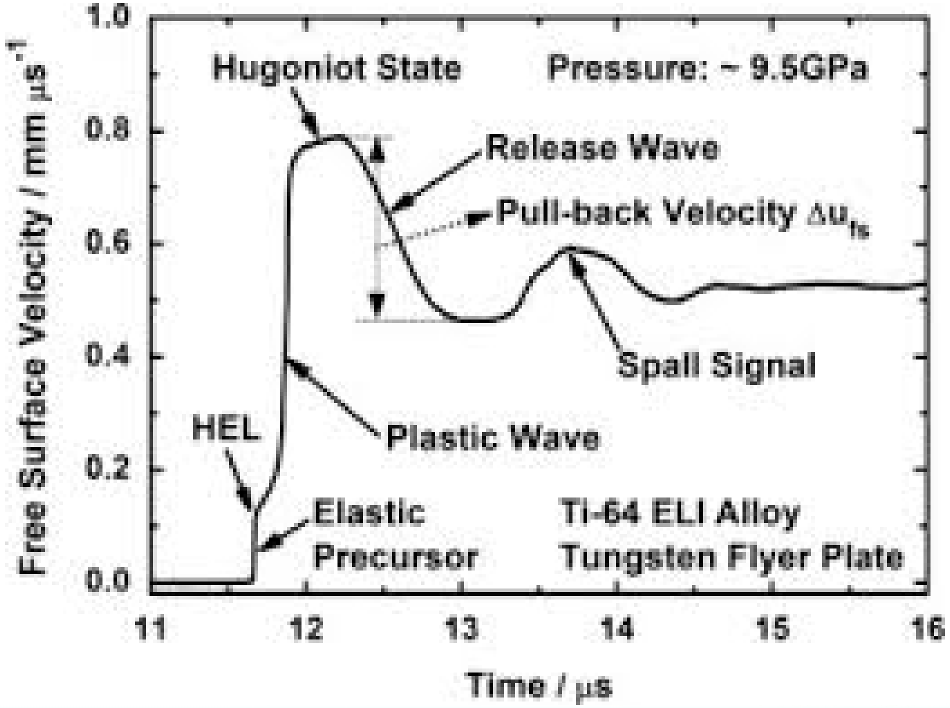
- Dynamic fracture phenomena:



Dynamic Spall Strength fracture phenomena is due to interacting decompression waves that produce a region of tension in the interior of the material.

- Testing:
  - Free surface velocity measured during spallation

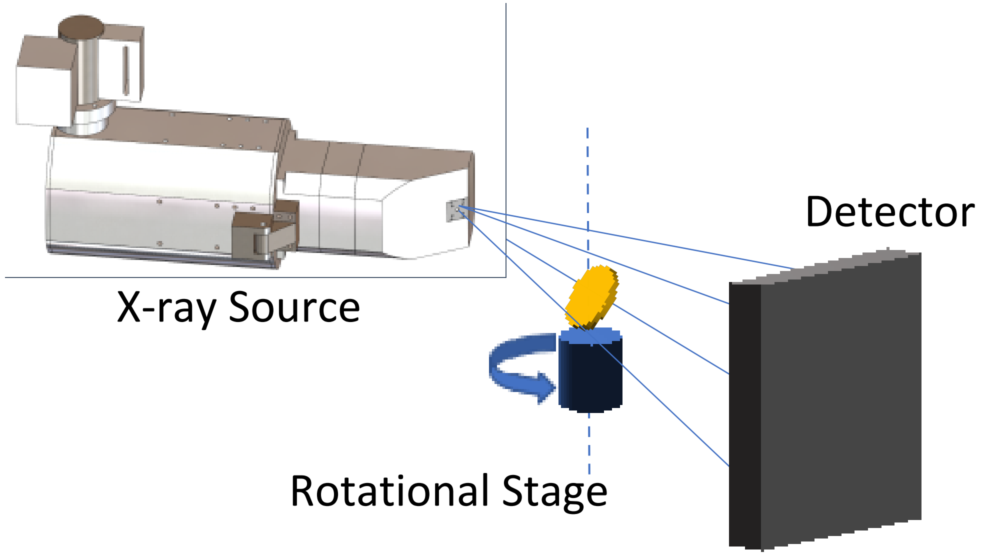


X-ray Inspection Setup:

- X-ray Computed Tomography:
  - Penetrating radiation is attenuated by AM material
  - Attenuated radiation is sampled at the flat panel detector and digitized into an image
  - Multiple images are taken at different angles while the part is spun 360 degrees

Sample	Titanium Ti5553 Disks scanned in sets of 5		
Energy	229 kV	Projections	3145
Amps	96 µA	Effective Pixel Size	21.13 and 36.47 µm
Magnification	5.48	Detector Type	VarionL08
Filter	N/A	X-ray Head Type	Nikon Microfocus XCT
Time	90 Mins	Frame Average	*6 Frames/projection*

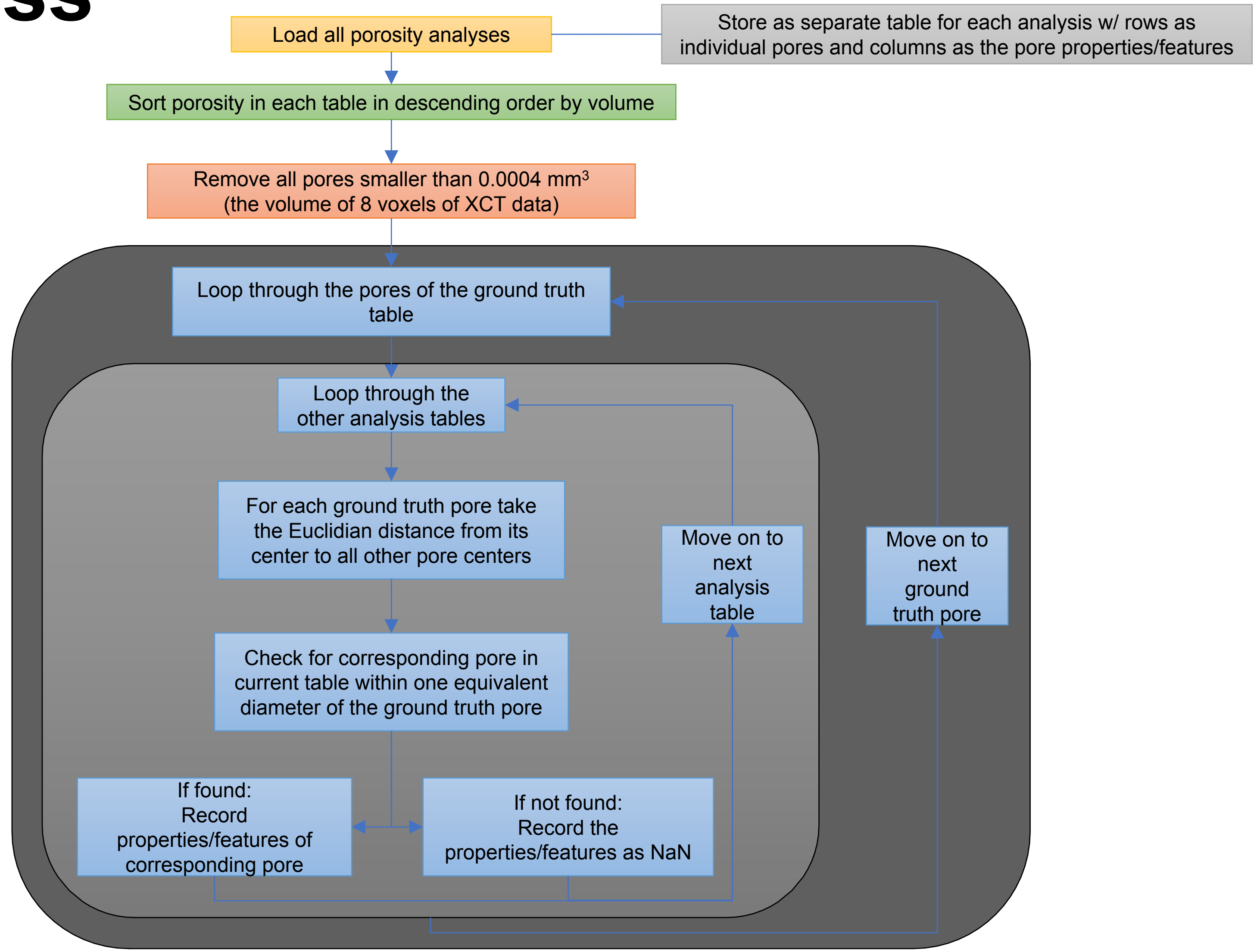
- Two dimensional images are reconstructed in a three dimensional data set (volume) that can be sliced in XY, YZ, and/or



Flow Chart of Process

- Quantification of Porosity Comparison:
  - Assignment of ground truth to ML segmented SS porosity
  - Systematic comparison of similar pores across inspection and analysis techniques

- Data Processing:
  - Serial sectioned slices were similarly processed for porosity
  - All porosity analysis results collected in VGStudioMax
  - Porosity Metrics exported to MatLab



Porosity Detection (Serial Sectioning versus ML):

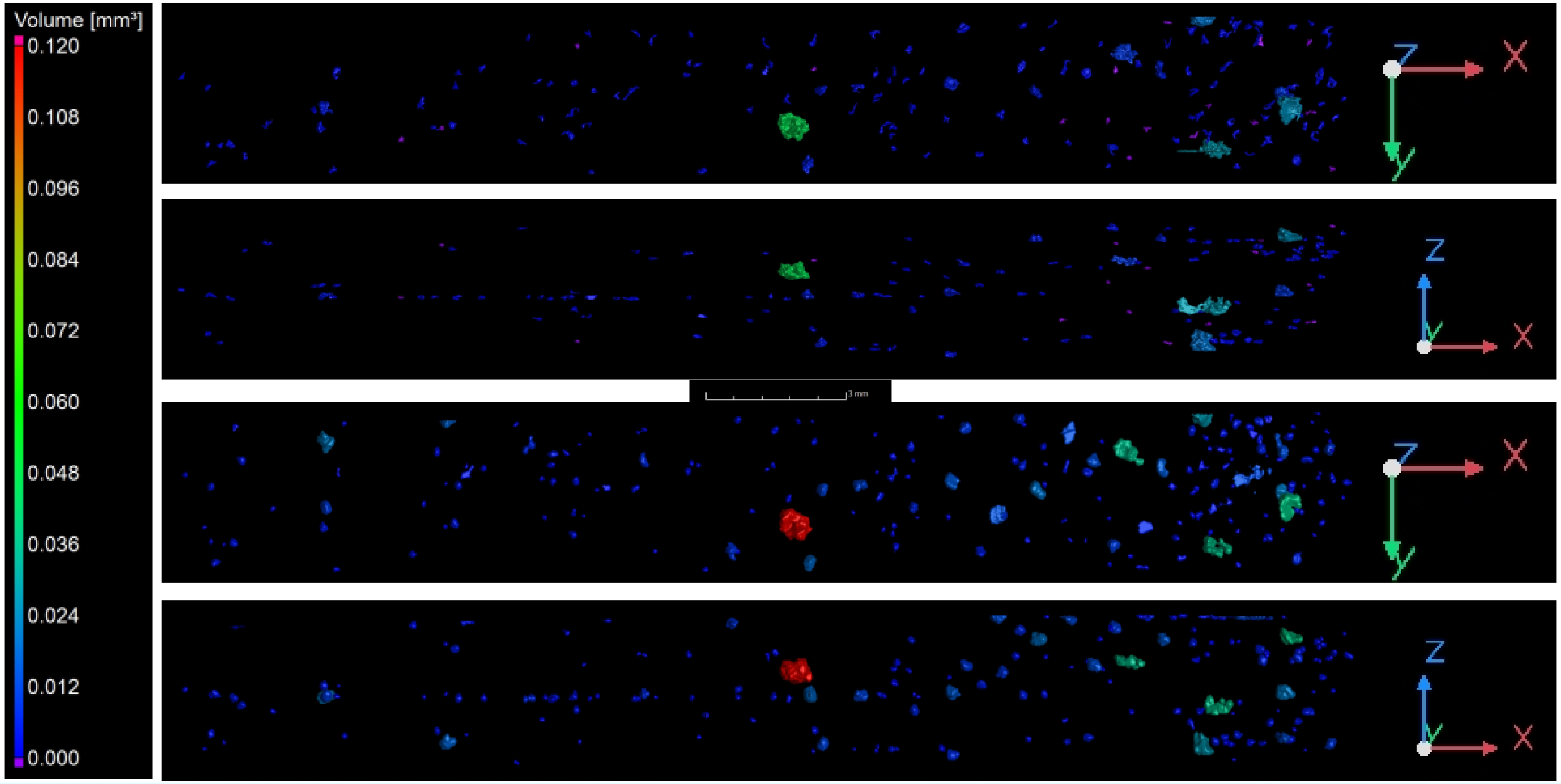
- Comparison of porosity between serial sectioning and XCT.

Serial Sectioning

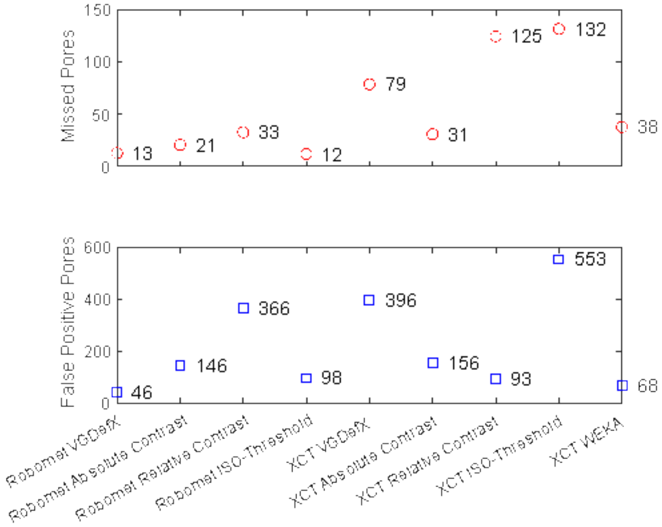
- Pores identified via machine learning

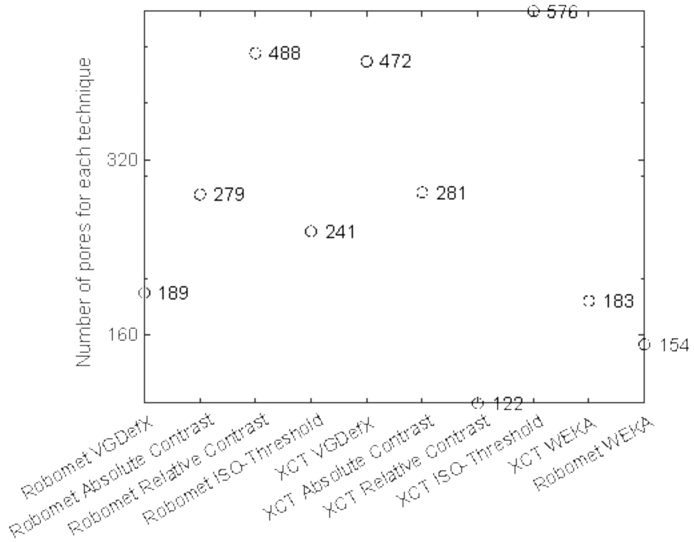
- SS images are not free of artifacts

XCT



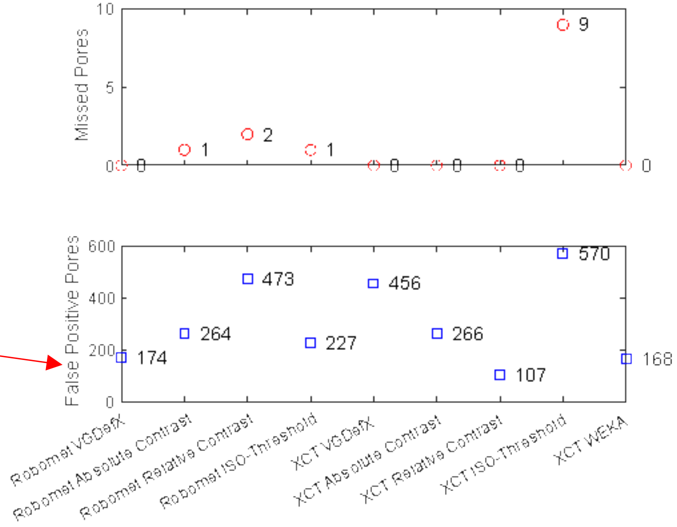
Comparing all pores greater than 0.0004 mm^3



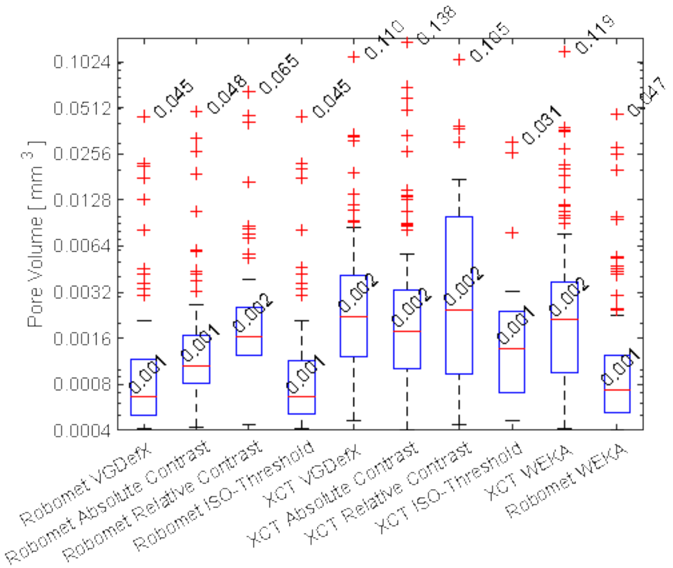


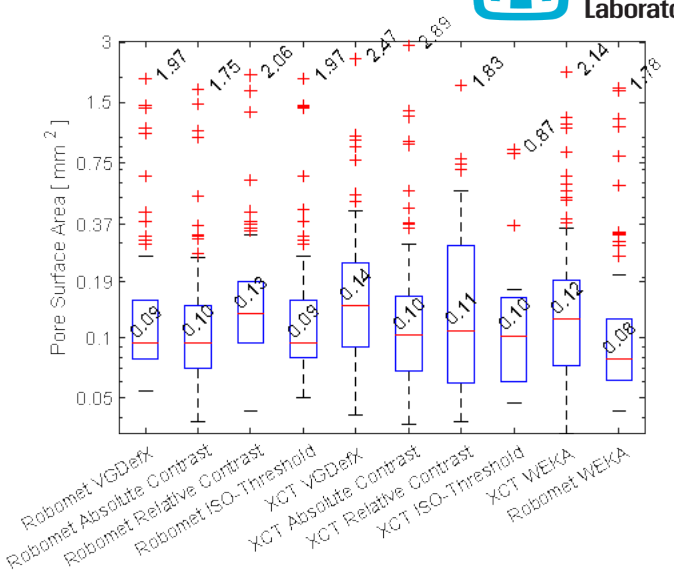
Comparing only the top 15 biggest pores

Notice the huge number of false positives here. The code is now saying anything not in those top 15 is a false positive

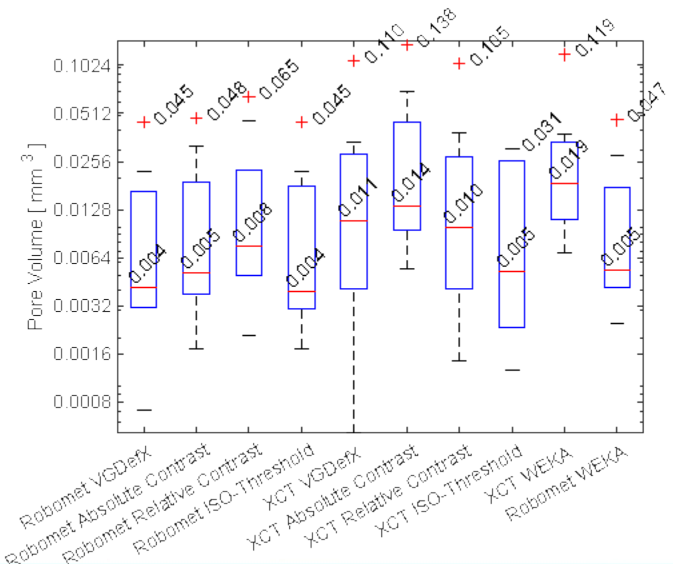


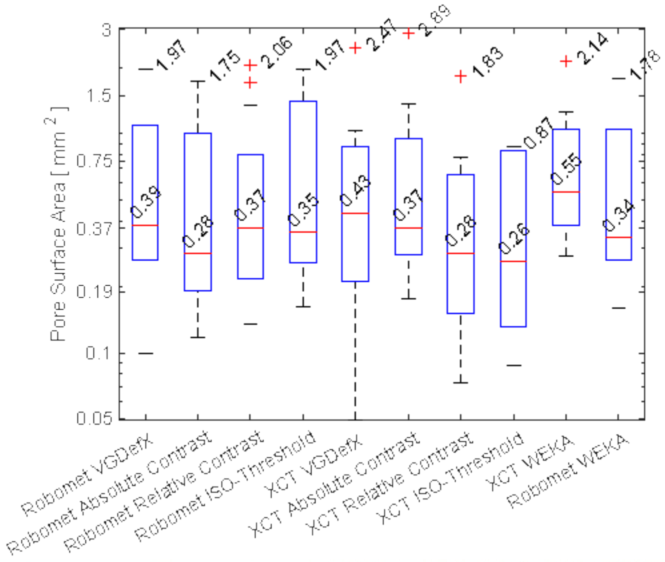
Comparing all pores greater than 0.0004 mm^3



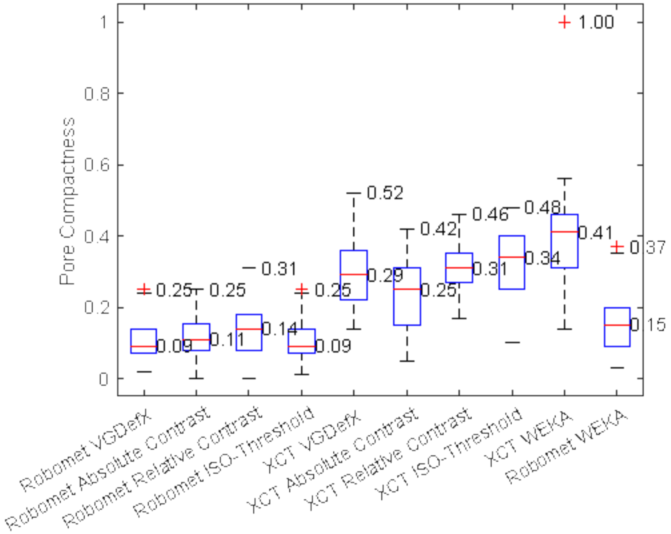


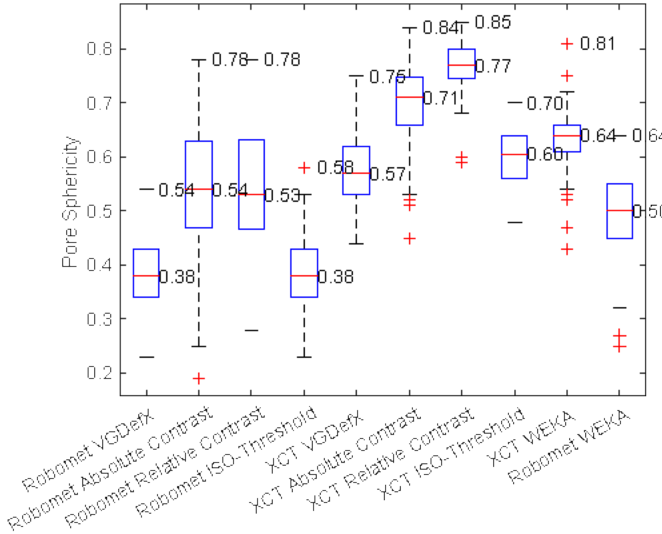
Comparing only the top 15 biggest pores



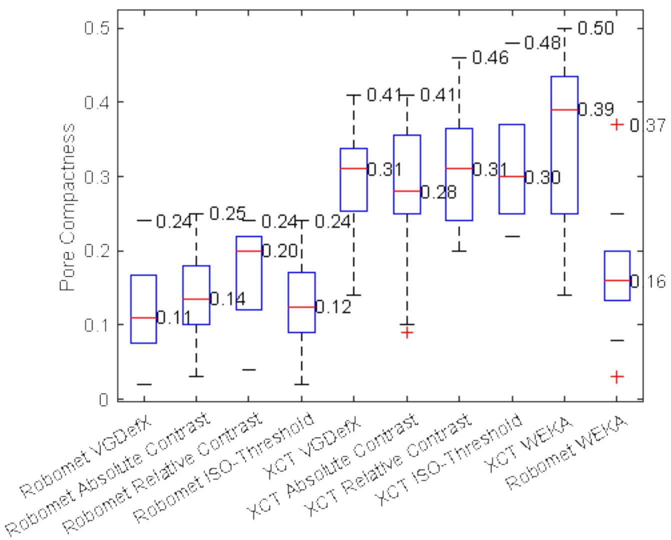


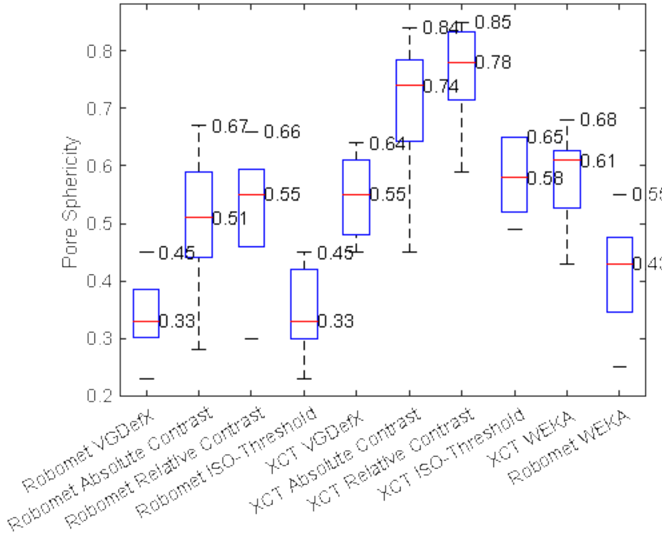
Comparing all pores greater than 0.0004 mm^3





Comparing only the top 15 biggest pores





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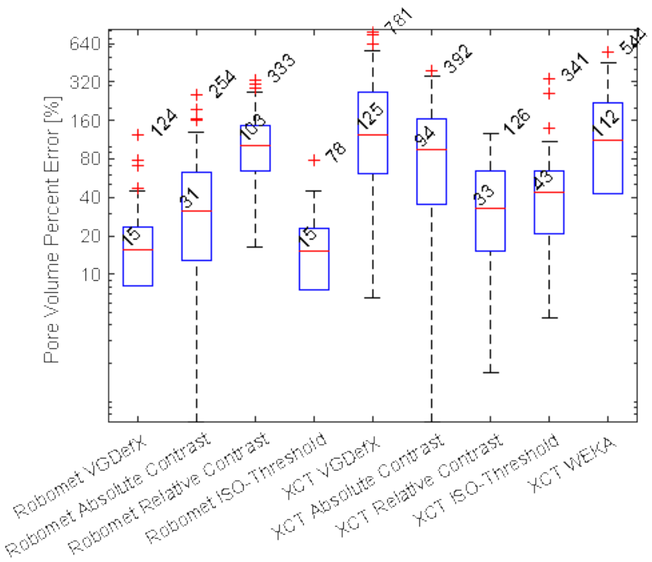
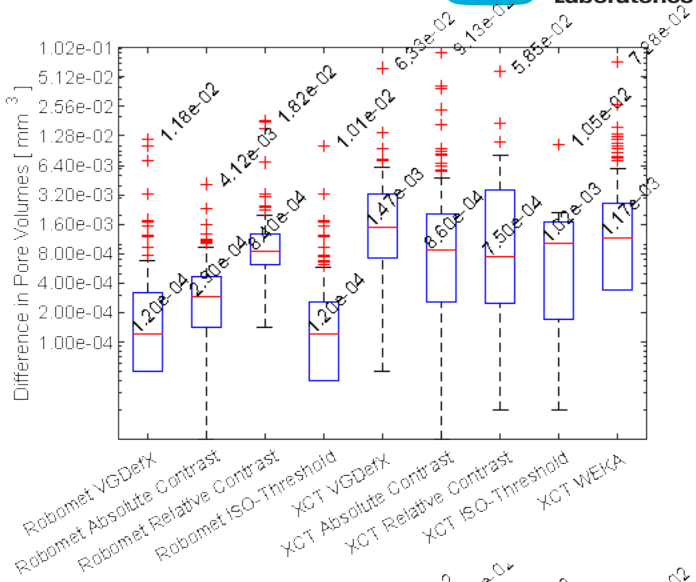
Comparing all pores greater than 0.0004 mm^3





Comparing only the top 15 biggest pores