In-situ, Layer-by-Layer, LPBF Monitoring with High Resolution Eddy Current Arrays

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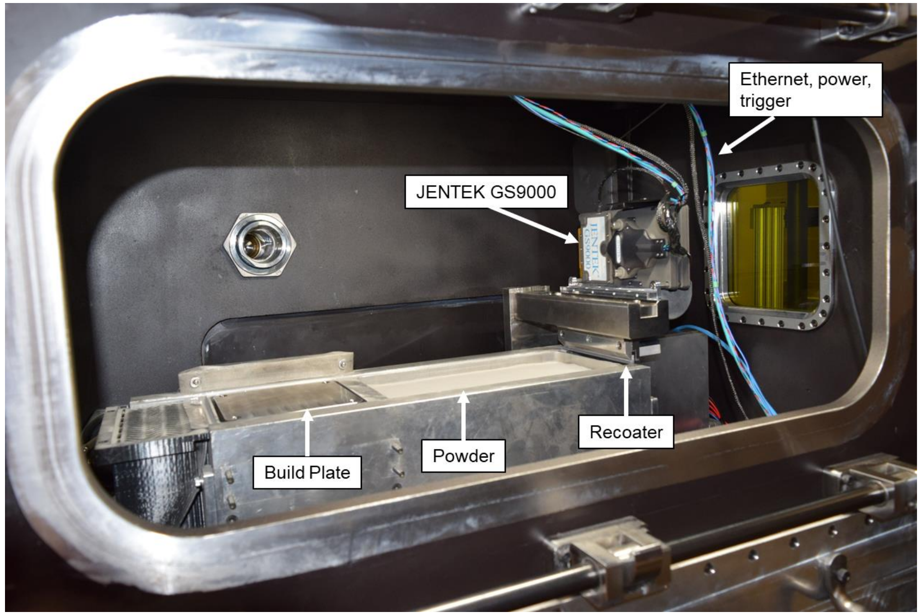
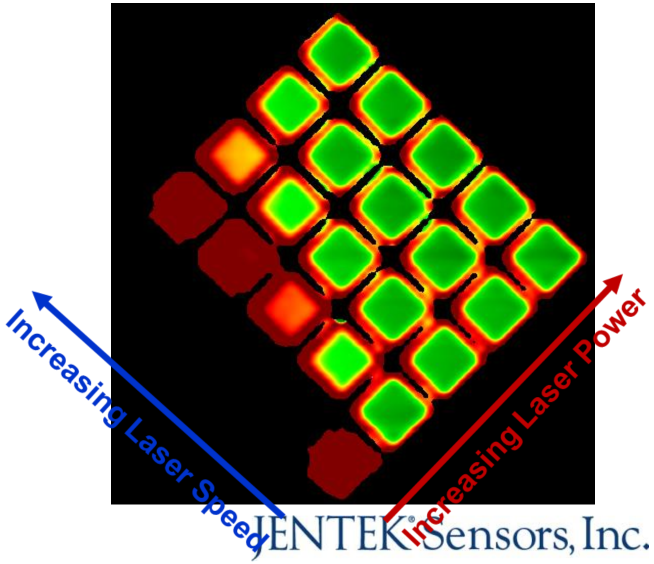
Agenda

- Introduction
- Eddy current technology overview
  - Eddy current fundamentals
  - Example instrumentation
  - Example installations
- Example results
  - UDRI DART 2 and GE M2 Series 5
  - Description of part builds and defect conditions
  - Data presentation (C-scans and B-scans)
  - Preferred direction (z-directed) filtering
- Powder characterization capabilities
- Summary

UDRI DART 2 Installation



Example GE M2 results (photo and measured conductivities)



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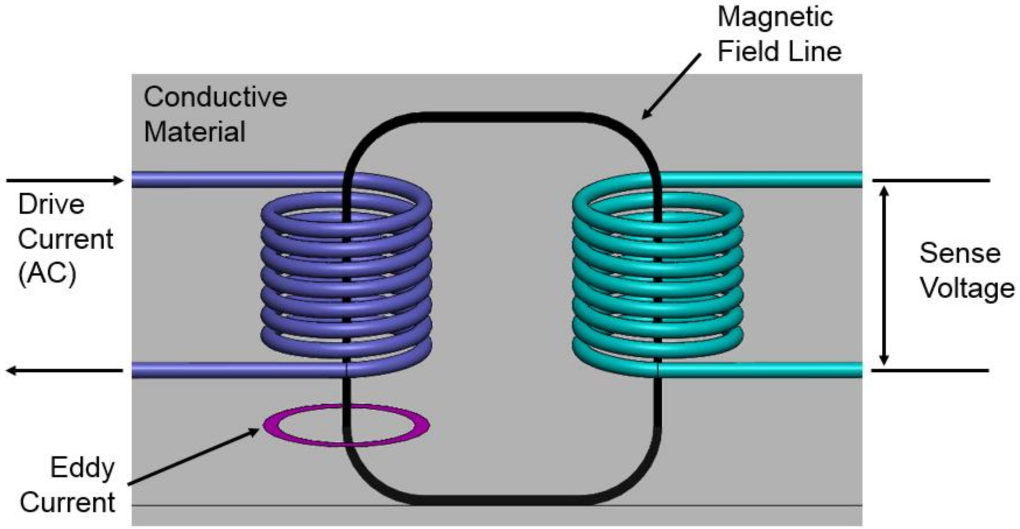
Introduction

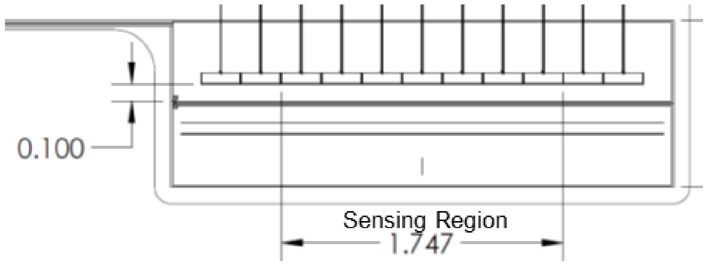
- Cost effective fabrication of qualified additively manufactured parts is a challenge
- Post-fabrication nondestructive testing (NDT) for quality assessment tends to be time consuming and expensive
- In-situ monitoring for relevant defect conditions has the potential to reduce costs and improve quality
  - Potential for reducing the need for post-fabrication NDT
  - Potential for in-situ repair with near real-time inspection assessment
- Two types of Probability of Detection (POD) are relevant
  - Discrete voids (important to detect sufficient size but of limited value because ever present)
  - Representative fabrication defects (lack of fusion, crack-like defects, and local metallurgical variations, but not easy to reproduce)
  - Need PODs with comparison to metallography and fatigue coupon testing for ranking of defect type and size effects based on performance impact
- Eddy current testing can address these in-situ monitoring needs
  - Conductivity correlation with properties of interest
  - Local defect detection using z-directed (preferred direction) filtering, prep for ML / AI
  - Sub-pixel geometric imaging for edges and small features

Eddy Current Background (1)

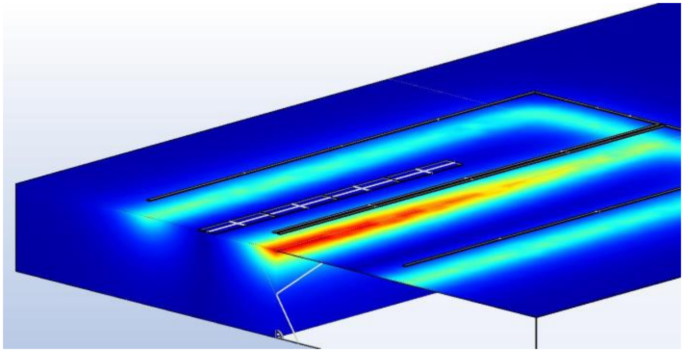
- Near-surface inspection method for magnetic and/or electrically conducting materials
  - Magnetic field produced by current in “drive” coils
  - Changing magnetic field induces eddy currents in nearby conductive materials
  - Voltage induced in sense coils by magnetic field from both drive coil and induced eddy currents
  - Measured voltage reflects material condition and geometry (e.g., electrical conductivity, magnetic permeability, porosity, wall and layer thickness)
- Advantages
  - Surface and near sub-surface defect and property sensitivity
  - Non-contact sensing
  - Not sensitive to relatively non-conducting and non-magnetic materials such as non-ferrous powders and typical contamination
  - Air calibration or reference material standardization
- Disadvantages
  - Near-field / close proximity required
  - Limited digital resolution
  - Direct connection between electronics and sensor required



Example linear array with single drive and multiple sense elements



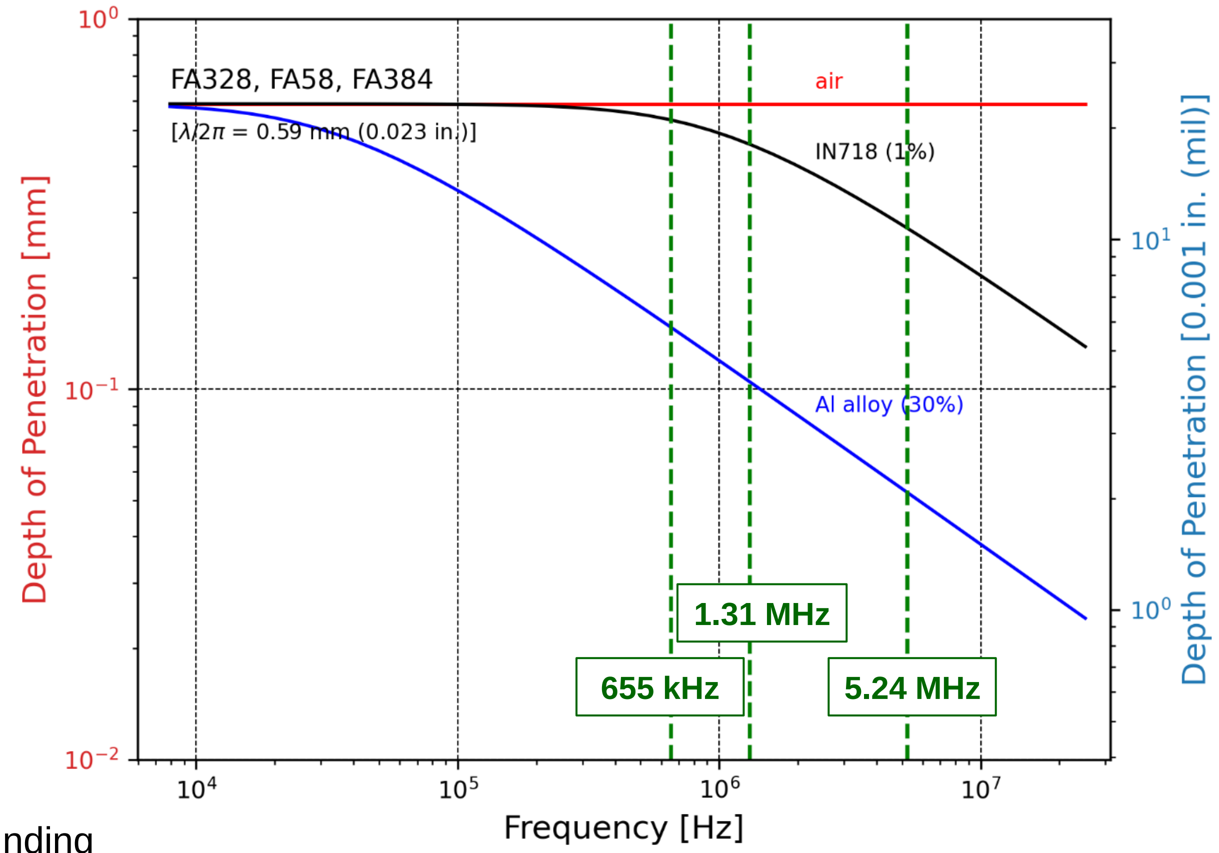
Example induced current density follows drive winding and penetrates into material



Eddy Current Background (2)

Depth of Penetration

- Magnetic fields decay approximately exponentially with distance away from drive winding
- Fields decay within each layer (e.g., air for noncontact measurements and test material)
- Decay rate in material determined by material properties and sensor geometry
- Depth of sensitivity can be 2-3 times depth of penetration

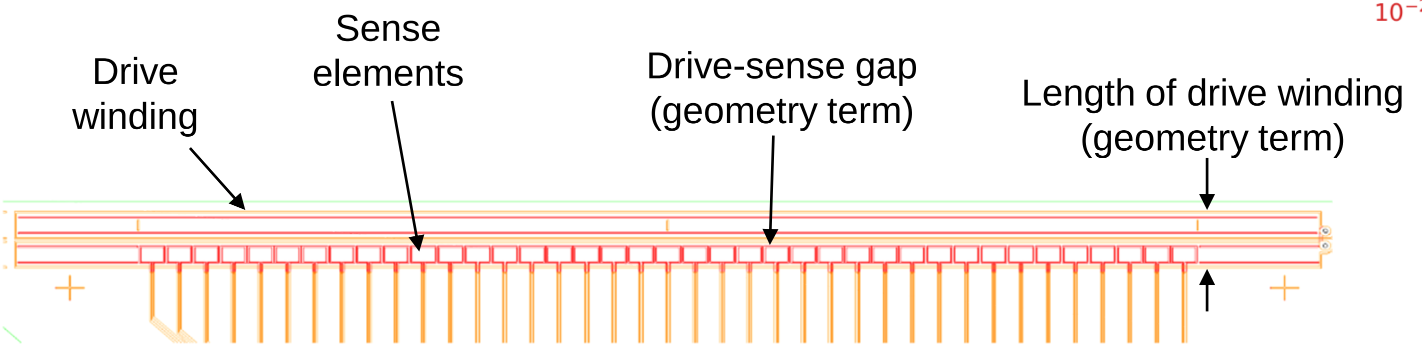


Geometry limited

Affects the lift-off that can be tolerated

Skin depth limited

Primary factor affecting field penetration into the metallic material under test

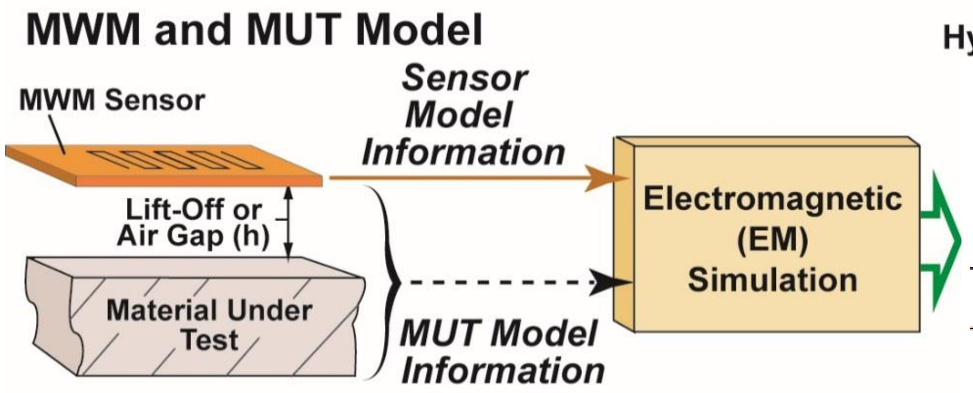


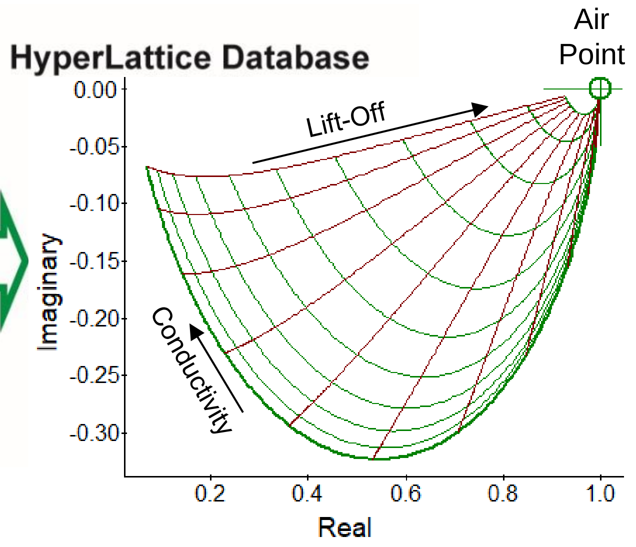
Example Eddy Current Array (MWM-Array)

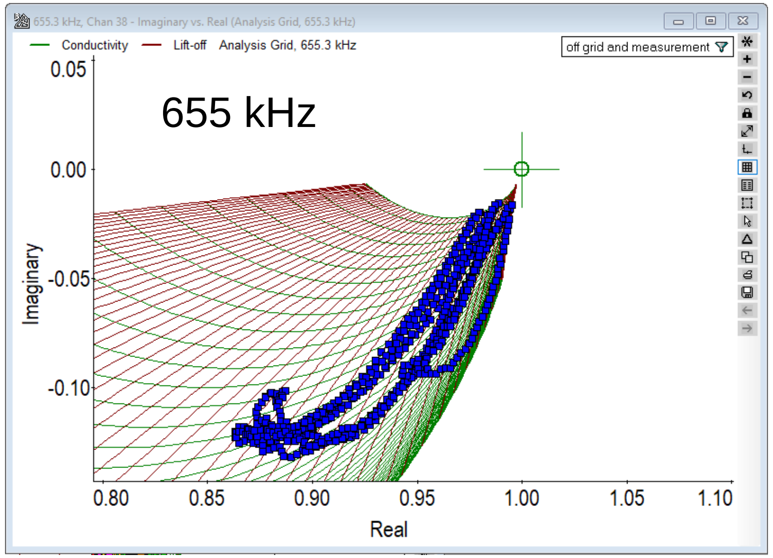
Eddy Current Background (3)

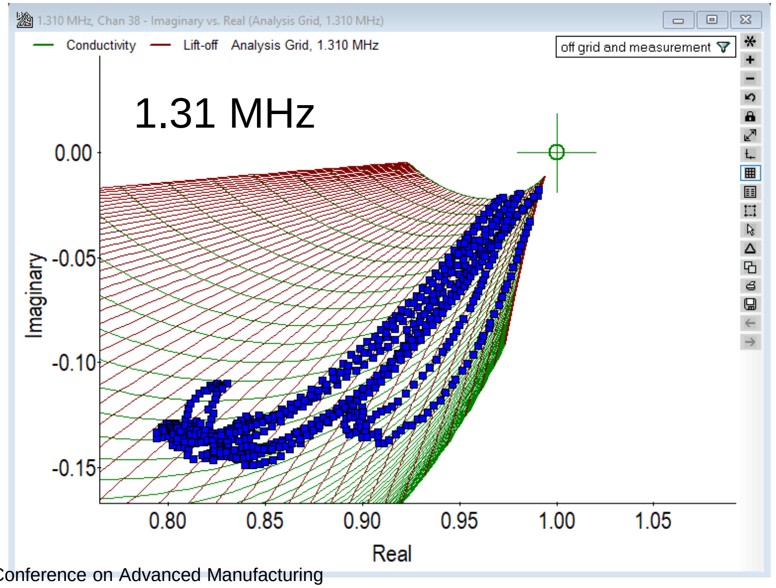
Property Estimation and Air Calibration

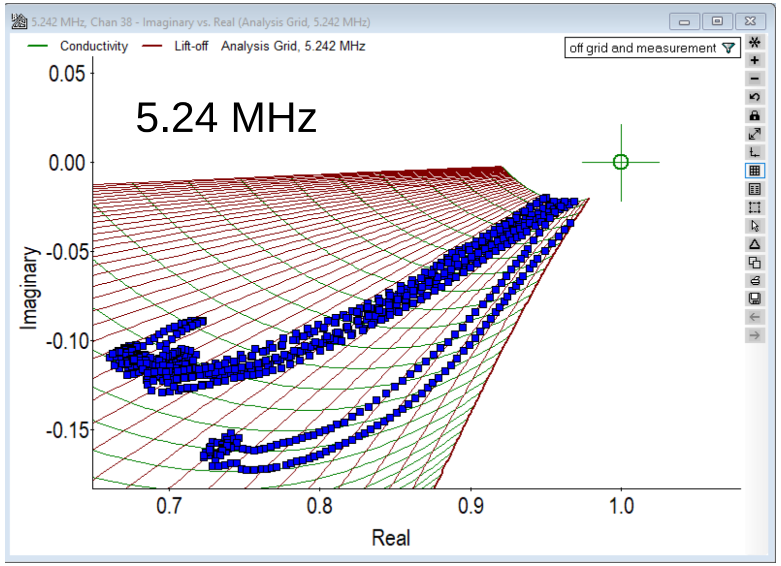
- MWM®-Array Sensors are designed to match models (i.e., predictable responses)
- Pre-computed databases enable independent measurement of conductivity and lift-off
- Re-calibration layer-by-layer optional
- Calibration verification within the build
- Sensor self-diagnostics through lift-off checks layer-by-layer











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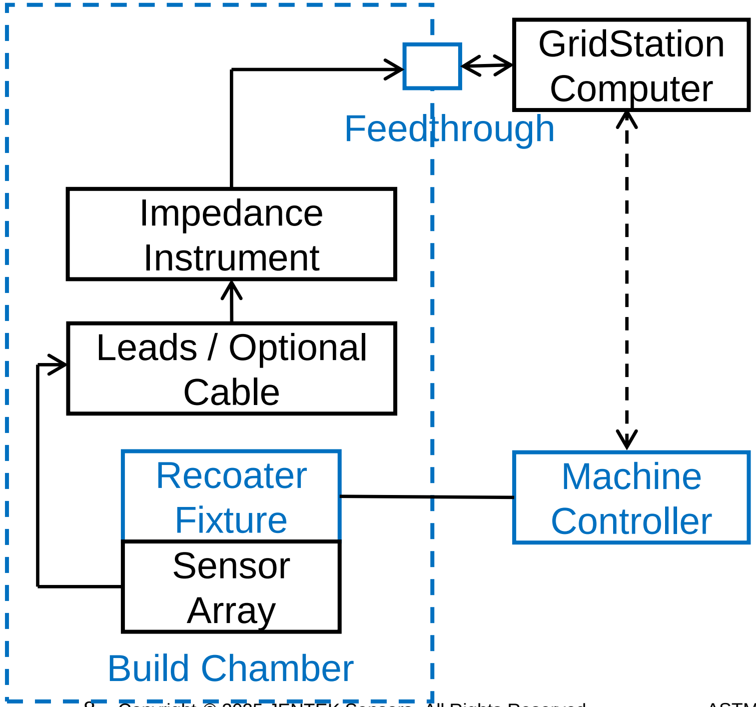
Eddy Current Equipment Installation (1)

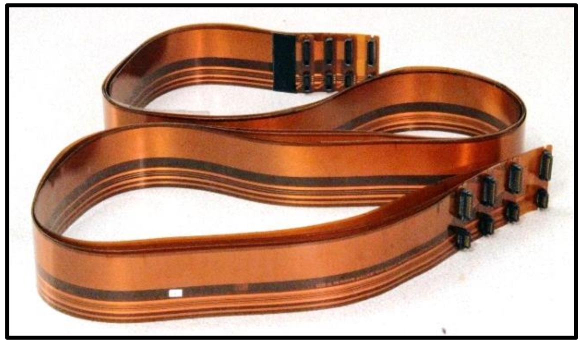
ASTM INTERNATIONAL ICAM25

- Elements of inspection system for GE M2 installation
- Some considerations:
  - Position encoder (account for non-constant recoater speeds)
  - Multiplexer, sense element size, and data acquisition rates
  - Impedance instrument location



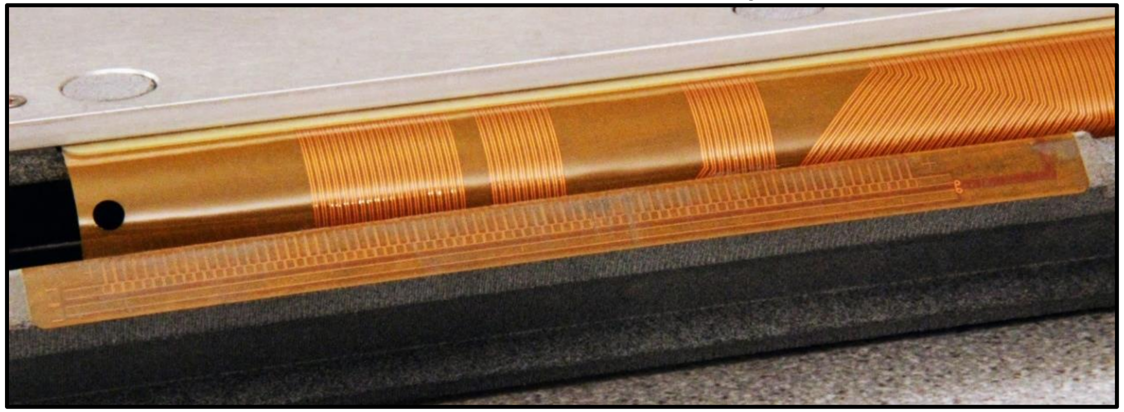
Sensor Mount Kit

Flex Cables (optional)

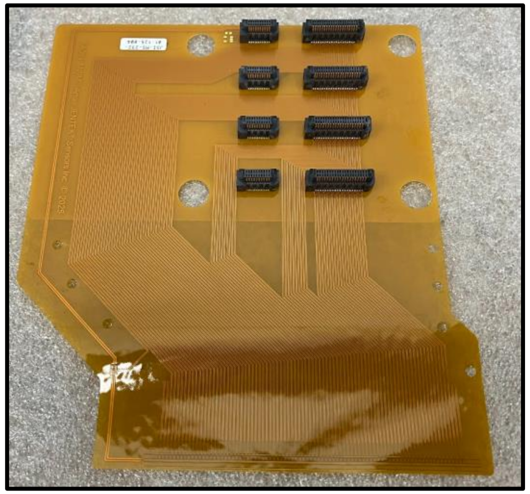


GS9000 Board Stack

79-Channel Sensor Array



79-Channel Sensor Array



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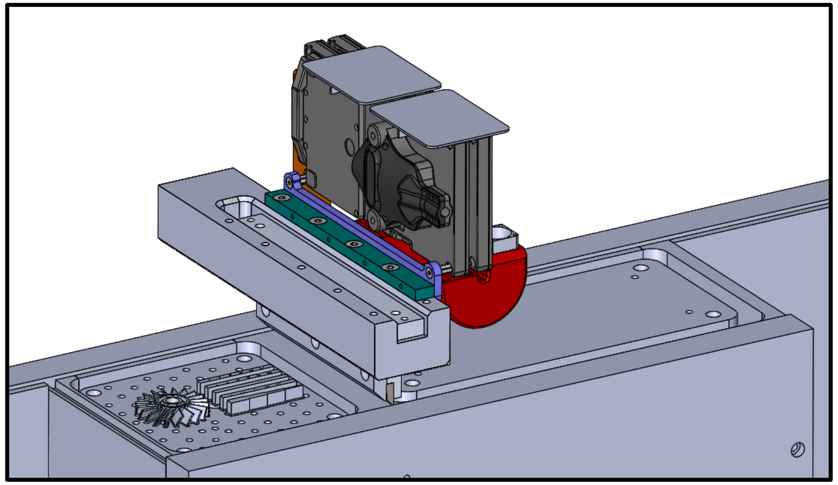
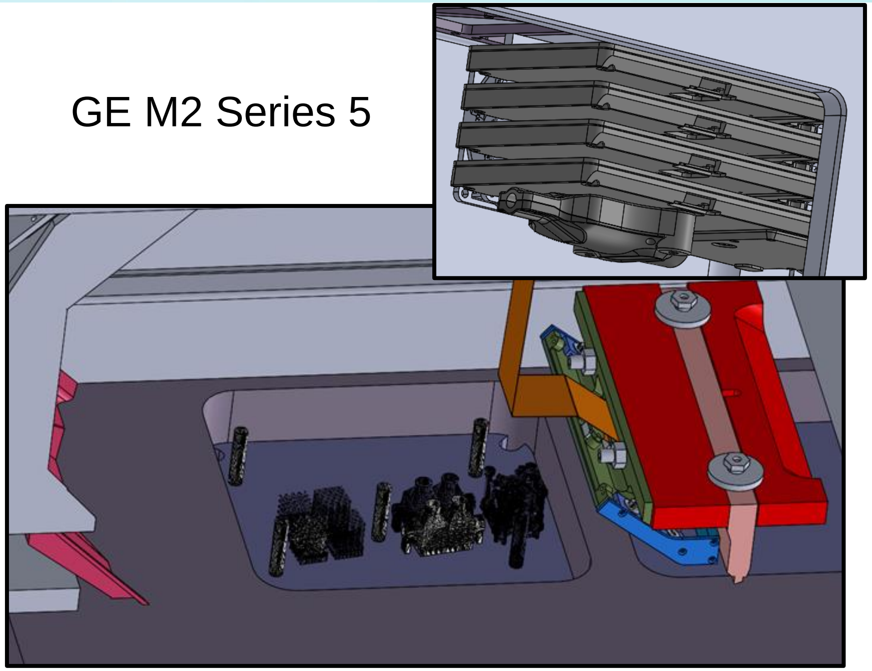
Eddy Current Equipment Installation (2)

- Machine agnostic approach
  - Only appropriate fixturing needed for different machines
- Data for all channels and for three frequencies recorded simultaneously
  - Enables local defect detection including defects surviving within prior several layers
- Rapid model-based multivariate physics solver
  - Enables air calibration
  - Enables rapid effective property (conductivity and lift-off) estimates
- Two installation configurations:
  - Instrument on recoater
  - Instrument on build chamber wall with flex cables to array

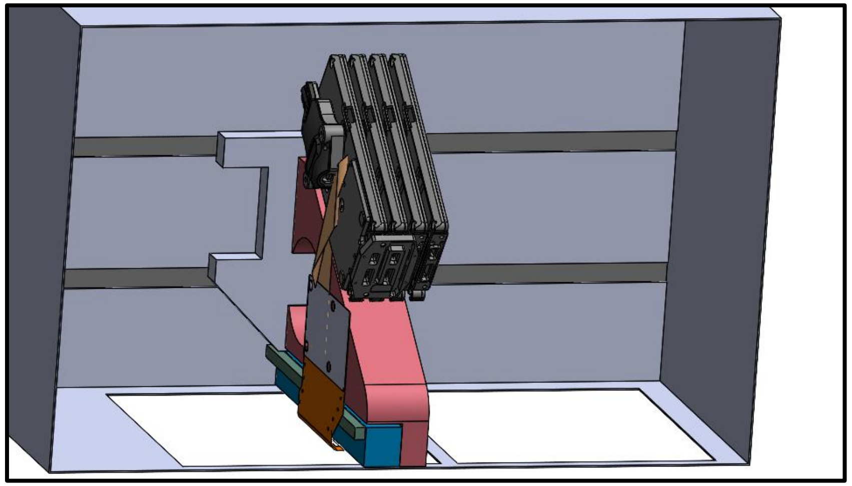
UDRI DART 2



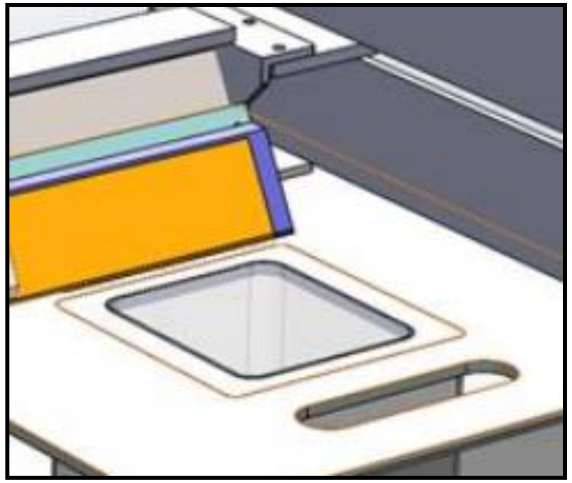
GE M2 Series 5



EOS 290 (planned)



SLM 125



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Relevant Eddy Current Standards

ASTM INTERNATIONAL | CAM25

- ASTM Committees
  - E07 (Nondestructive Testing)
  - F42 (Additive Manufacturing Technologies)
- Standards
  - E1004 (Test Method for Determining Electrical Conductivity Using the Eddy Current Method)
  - E2338 (Practice for Characterization of Coatings Using Conformable Eddy Current Sensors without Coating Reference Standards)
  - E2884 (Guide for Eddy Current Testing of Electrically Conducting Materials Using Conformable Sensor Arrays)
  - E3166 (Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build)

INTERNATIONAL

Designation: E2338 – 22

Standard Practice for Characterization of Coatings Using Conformable Eddy Current Sensors without Coating Reference Standards[1]

This standard is issued under the fixed designation E2338; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This practice covers the use of conformable eddy current sensors for nondestructive characterization of coatings without standardization on coated reference parts. It includes the following: *(1)* thickness measurement of a conductive coating on a conductive substrate, *(2)* detection and character-

ization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

INTERNATIONAL

Designation: E2884 – 22

Standard Guide for Eddy Current Testing of Electrically Conducting Materials Using Conformable Sensor Arrays[1]

This standard is issued under the fixed designation E2884; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This guide covers the use of conformable eddy current sensor arrays for nondestructive examination of electrically conducting materials for discontinuities and material quality. The discontinuities include surface breaking and subsurface

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E543 Specification for Agencies Performing Nondestructive Testing

E1316 Terminology for Nondestructive Examinations

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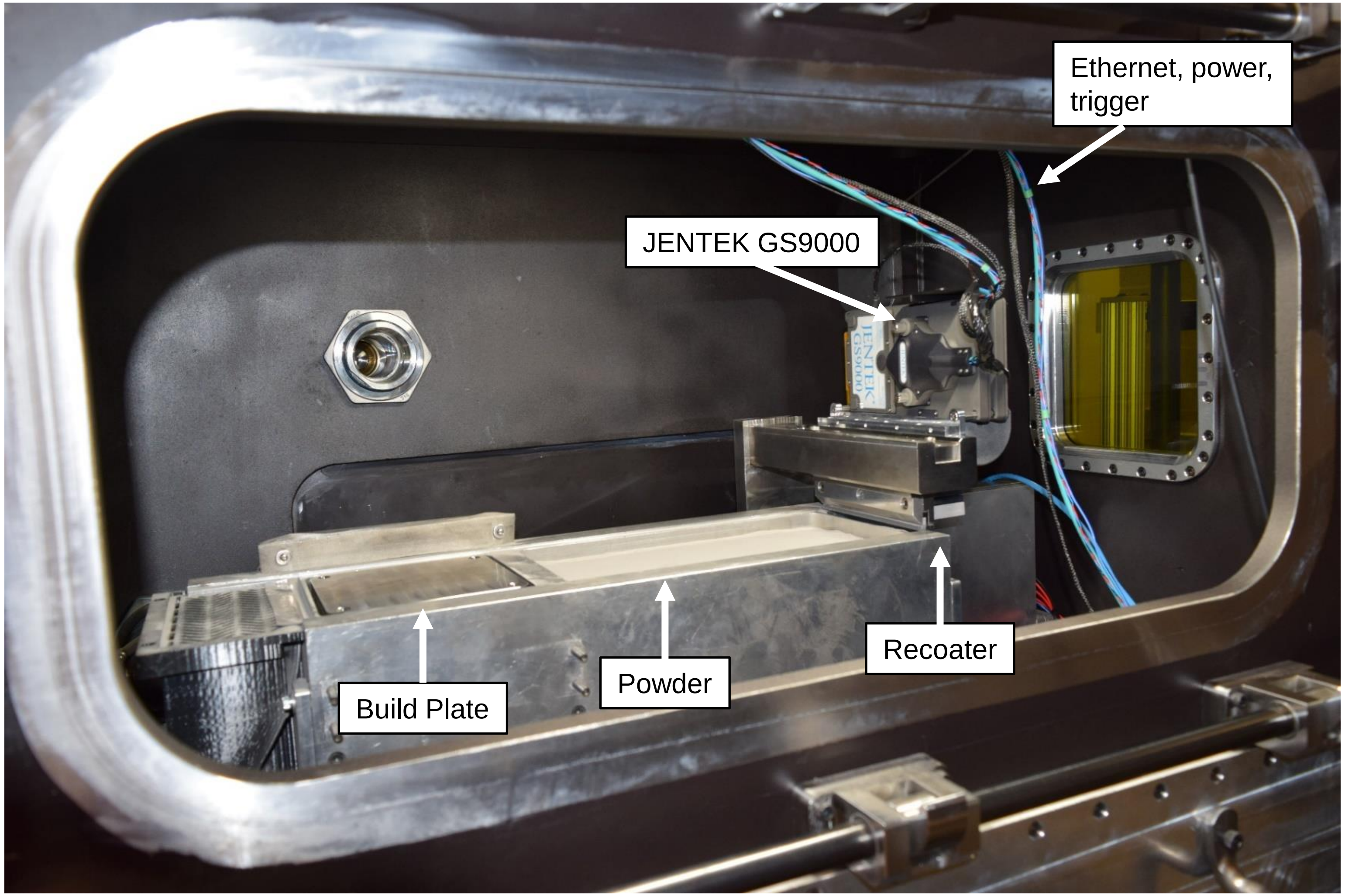
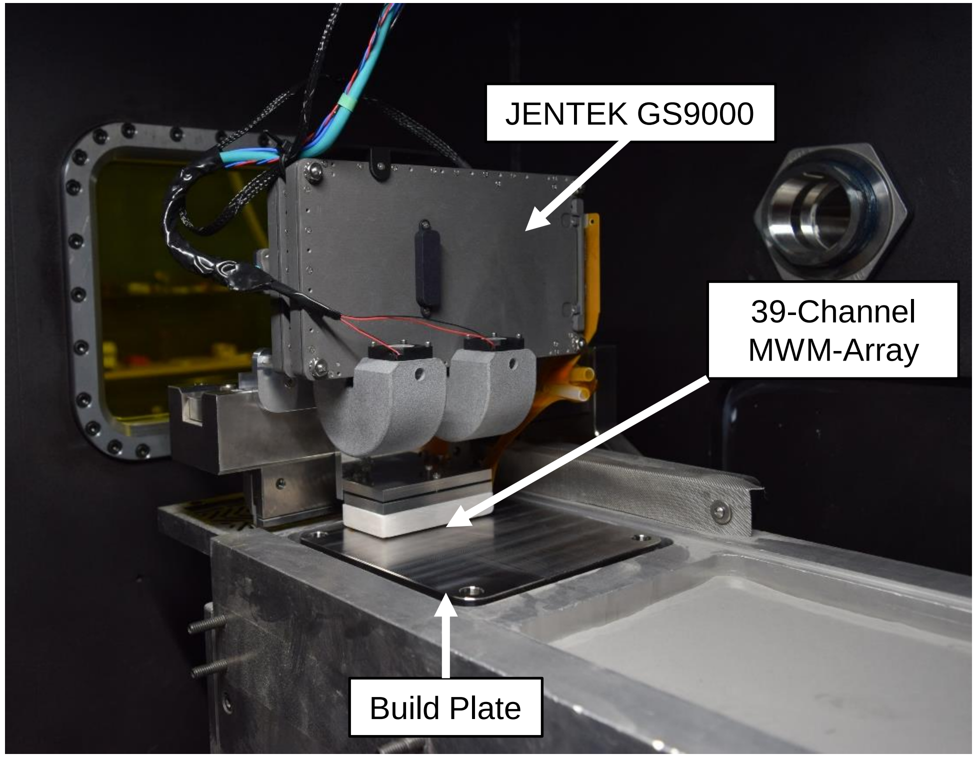
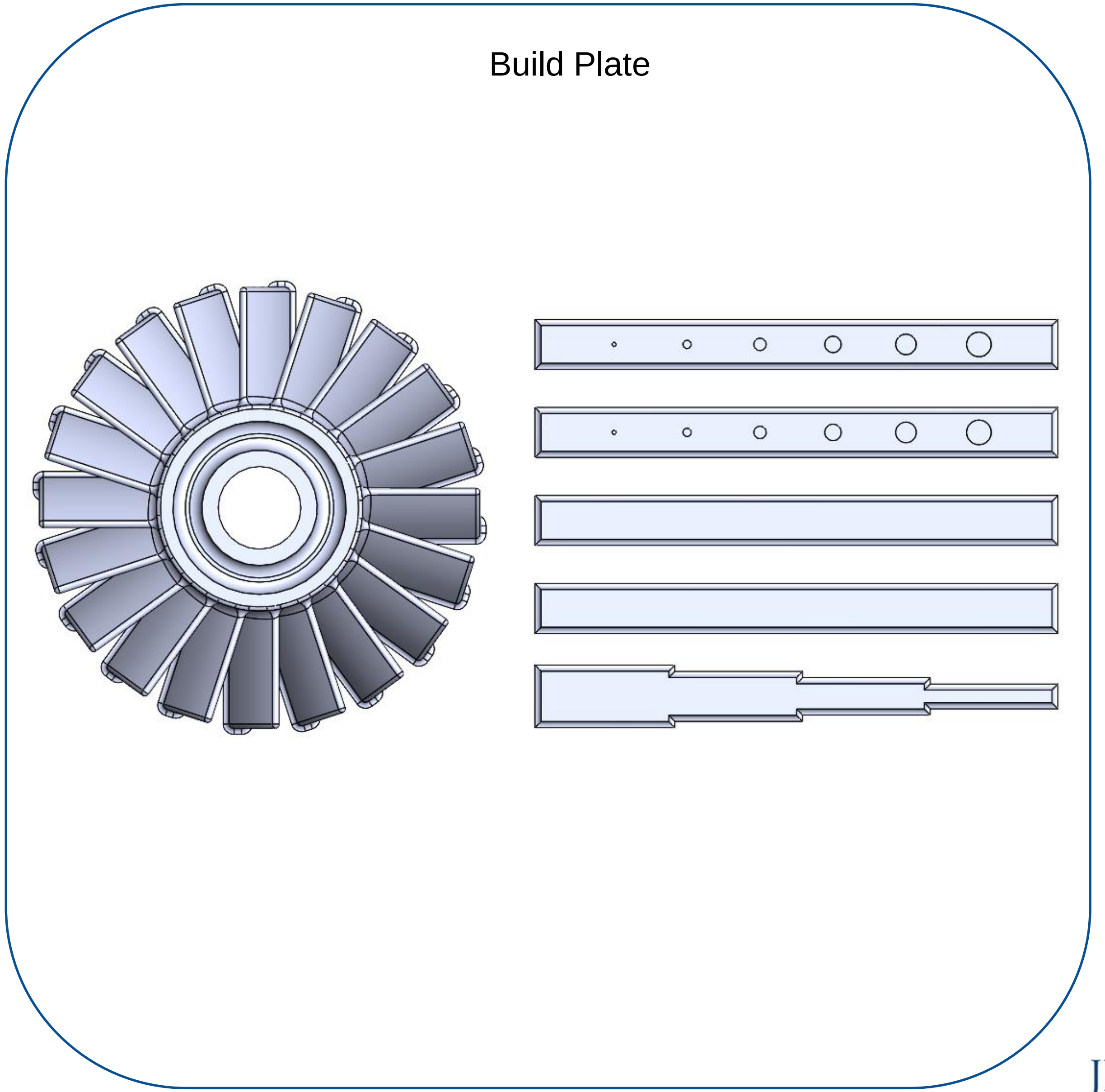
UDRI DART 2 Configuration (1)



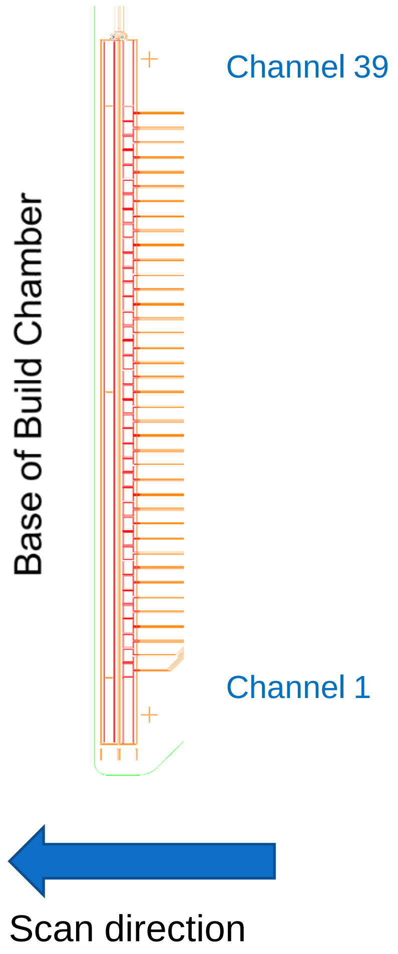


UDRI DART 2 Configuration (2)

- Scan speed: ~ 100 mm/sec [4 in./sec]
  - did NOT alter standard motion rate for recoater
- Data Rate: ~ 0.1 mm [0.004 in.]
  - Increments in scan direction
- Frequencies: 655 kHz, 1.31 MHz, 5.24 MHz
  - Demonstrated 10.5 MHz in other builds
- Sensor array: FA358 MWM-Array
  - 39 sense elements
  - Channel direction size = 1.5 mm [0.06 in.]
  - Recoat direction size = 1.0 mm [0.04 in.]
  - Scan width of MWM-Array: 59.4 mm [2.34 in.]
- Build details:
  - Material: nickel alloy 718
  - Layer Thickness: 40 microns [0.0016 in.]
  - Build plate size (for DART 2): 152 mm x 152 mm [6 in. x 6 in.]
  - Number of Layers: 249
- Air calibration
  - Performed with sensor array in air at start of build
  - Can recalibrate for each layer/scan
- File size: 5GB for basic property estimates
  - for 250 layers and 22 in. scan



MWM-Array mounted to recoater



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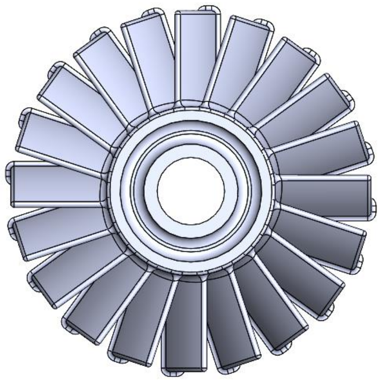
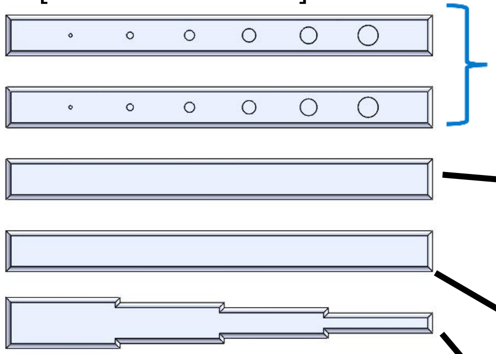
UDRI DART 2 Build Details

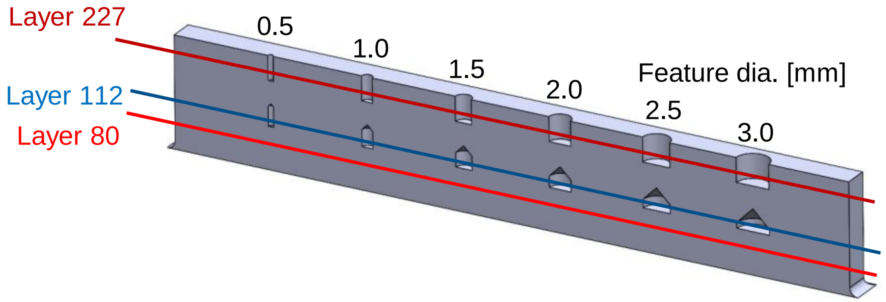
249-layer build of nickel alloy 718.
Bars are 10 mm [0.394 in.] tall.

Example complex shaped part

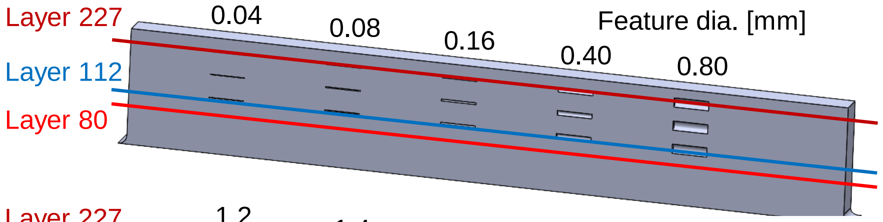


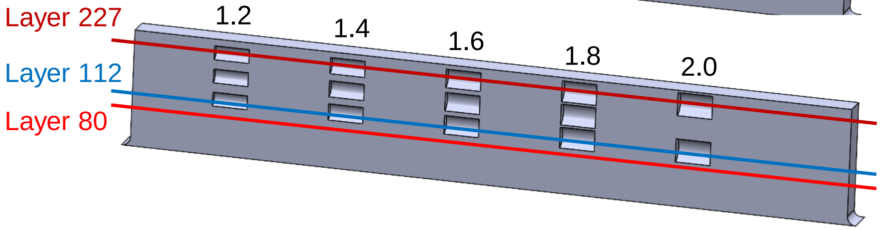
Each bar is 62 mm x 4.6 mm
[2.44 in x 0.180 in.]



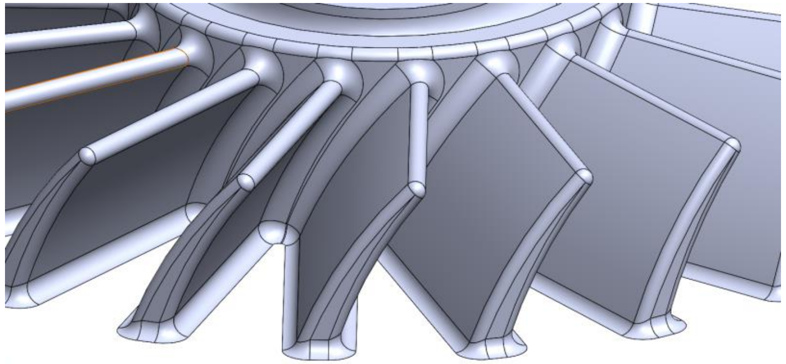


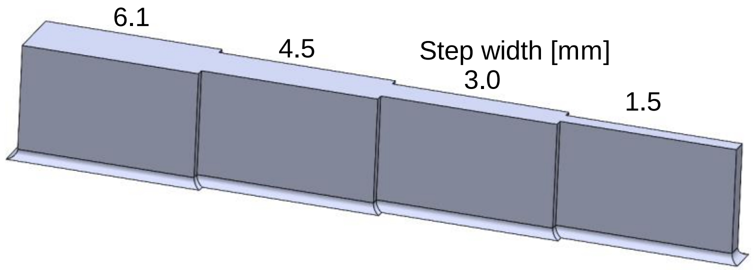
Bars 1 and 2:
Lower voids 2.00 mm [0.05 in.] tall and chamfered.
Upper voids 2.19 mm [0.056 in.] tall and surface breaking. 2 mm [0.05 in.] solid metal between upper and lower voids.





Bars 3 and 4:
All voids are 3 mm [0.076 in.] in length with 7 mm [0.180 in.] spacing.

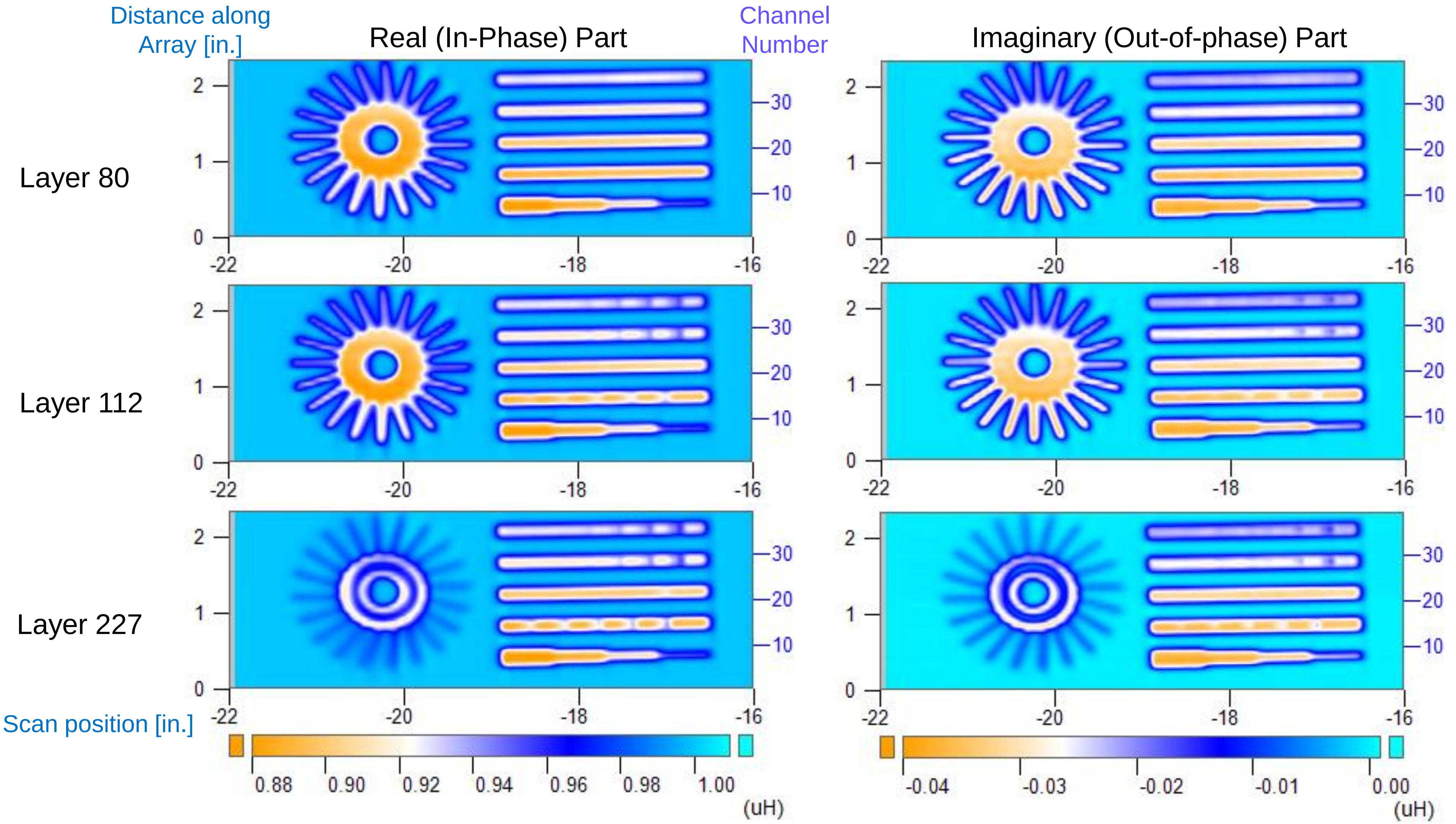


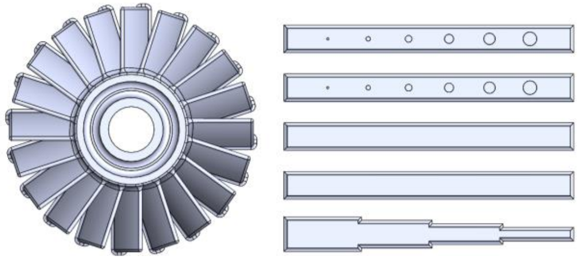


Bar 5: Stepped taper. Each step is 15.5 mm [0.609 in.] long.

UDRI DART 2 Results (1)

- Example 5.24 MHz, Impedance Data
  - Similar results at other frequencies
  - No post-processing (other than image mapping)
  - Shows general geometry and larger defect conditions





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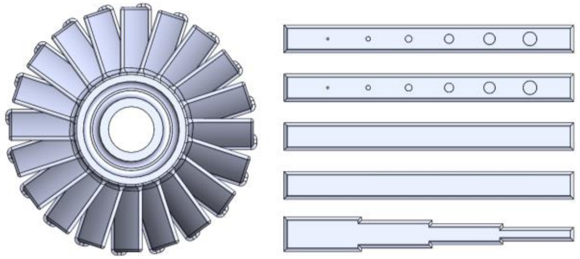
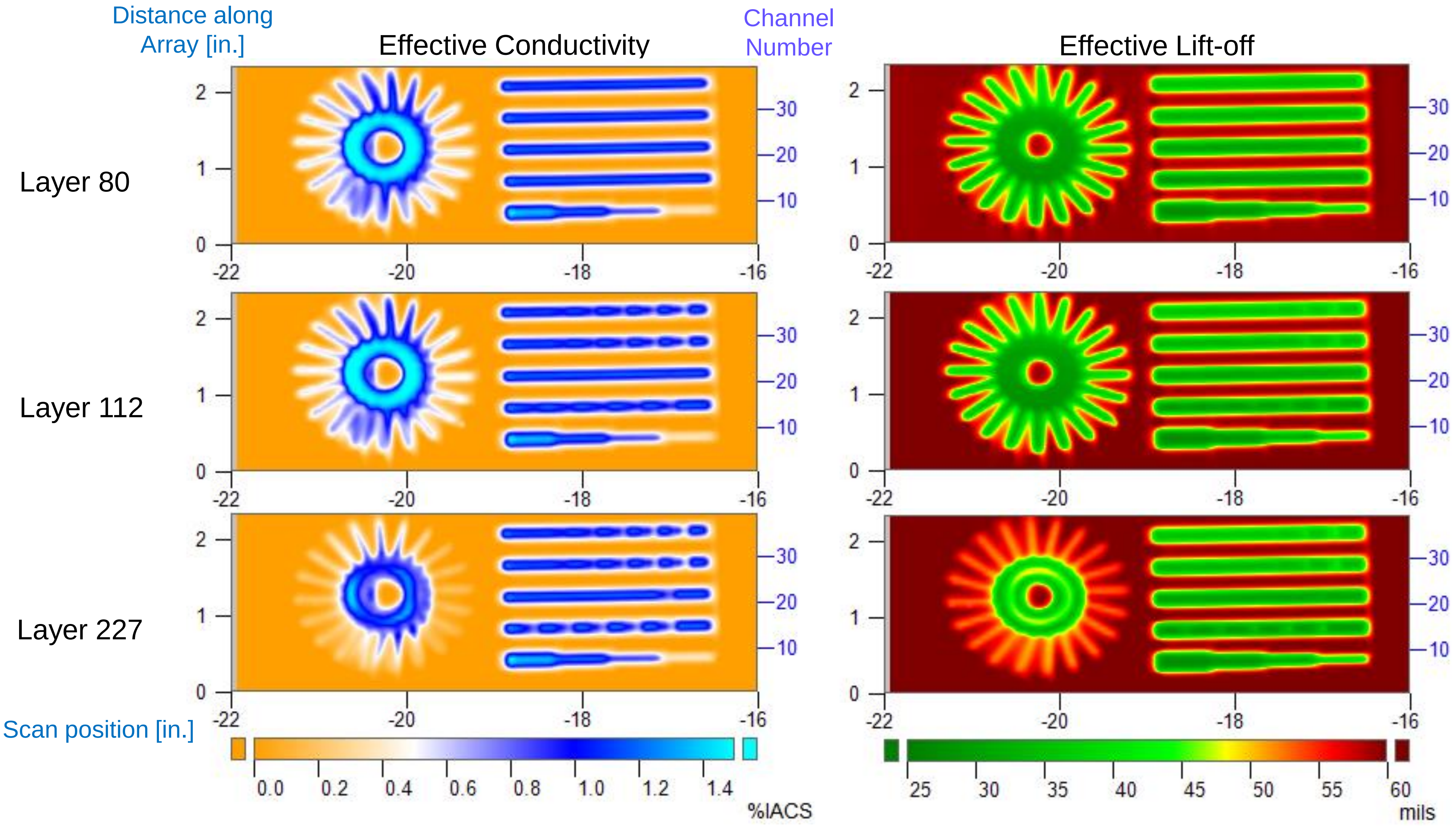
UDRI DART 2 Results (2)

- Example 5.24 MHz, Property Data
  - Similar results at other frequencies
  - Minimal processing (4 sec/layer)
  - Effective properties obtained from standard layered media models
  - Suitable for larger build regions
  - Can be adapted to account for thin wall regions





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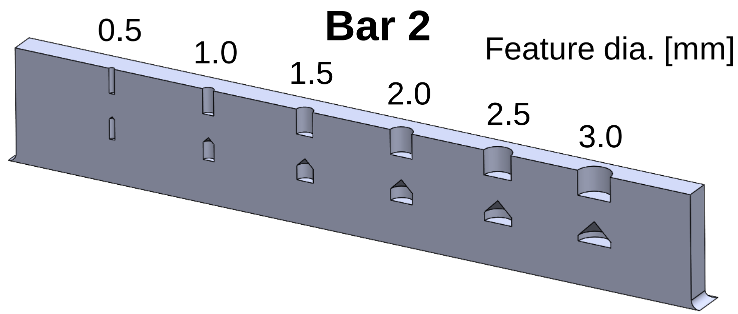
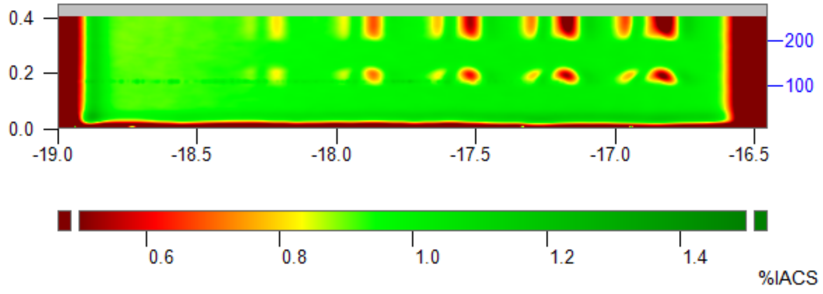
UDRI DART 2 Results (3)

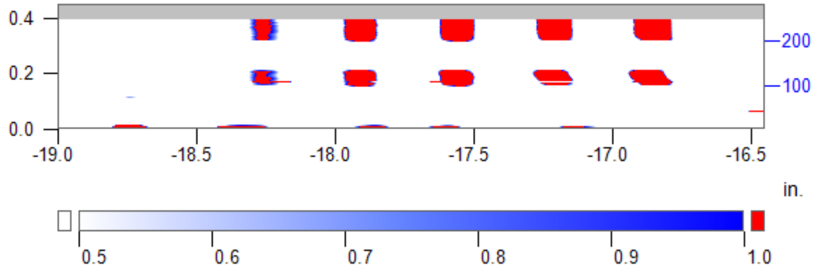
– Example Vertical Slices

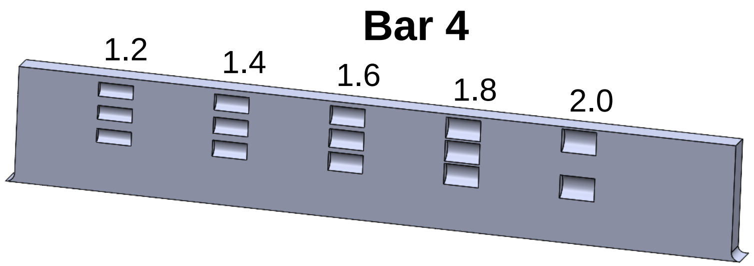
Effective Conductivity | Simple Shape Filter (5 MHz only)



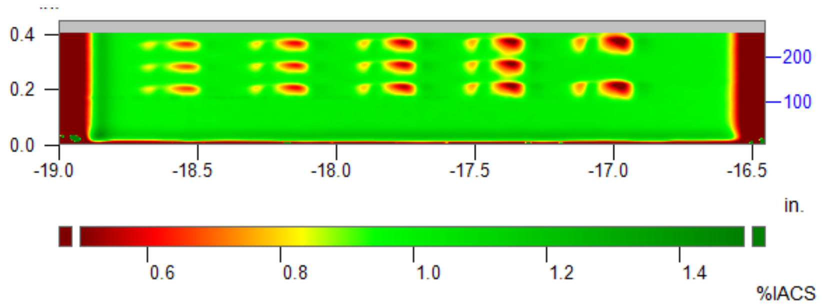
Bar 2 (Chan 29)

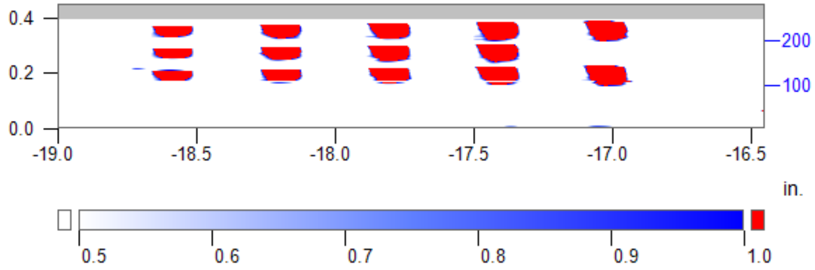






Bar 4 (Chan 15)





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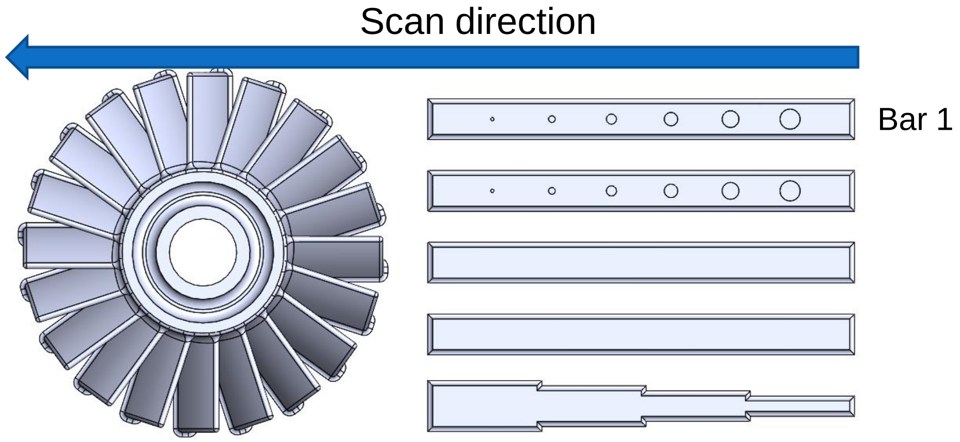
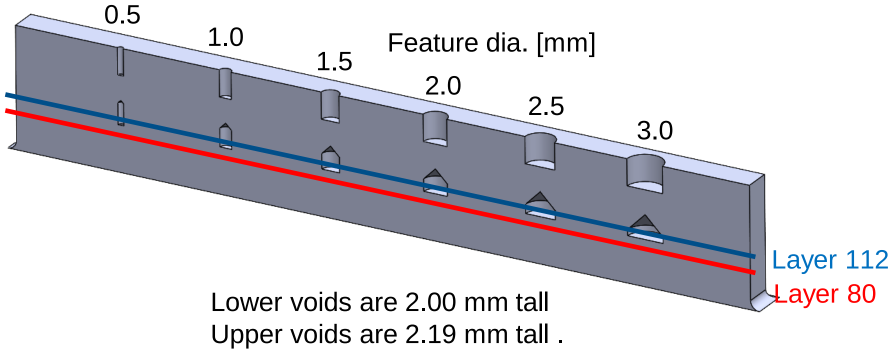
UDRI DART 2 Results (4)

- Example B-scan plots
  - Take advantage of higher spatial resolution in scan direction compared to channel direction
  - Distinctive shapes associated with discrete flaws and edges
  - Can assess data in impedance space as well as property space

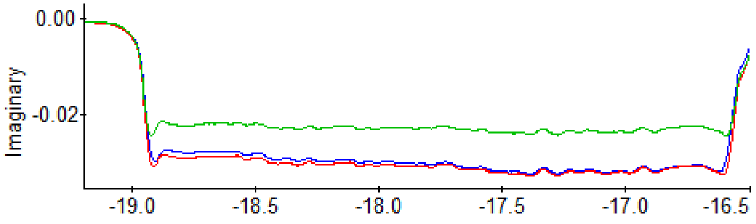


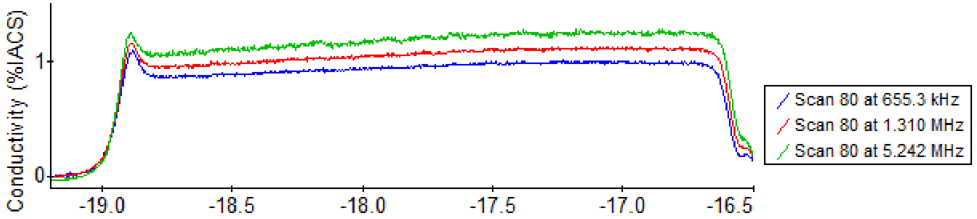


Bar 1: Channel 36

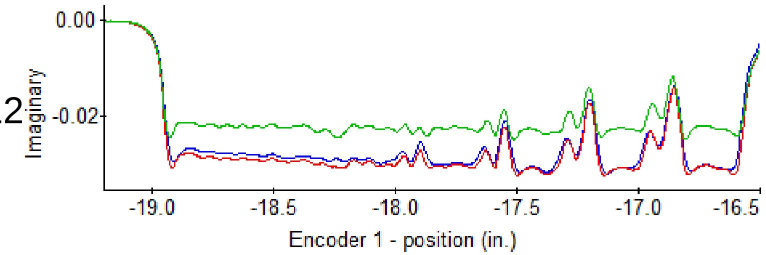
Bar 1: Channel 36

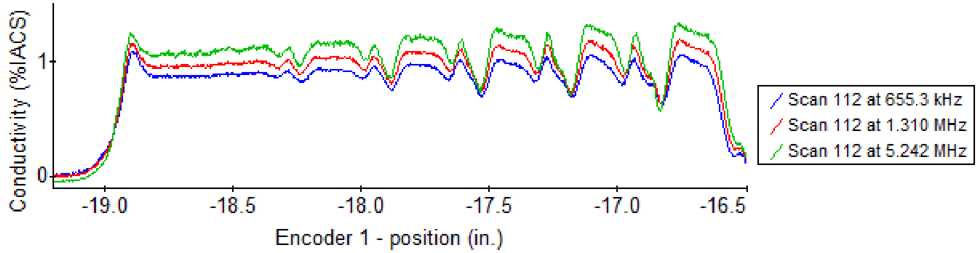
Layer 80





Layer 112





Void conditions visible – can use raw impedance data or effective property estimate data for analysis. Effective properties most useful when the geometry is modeled

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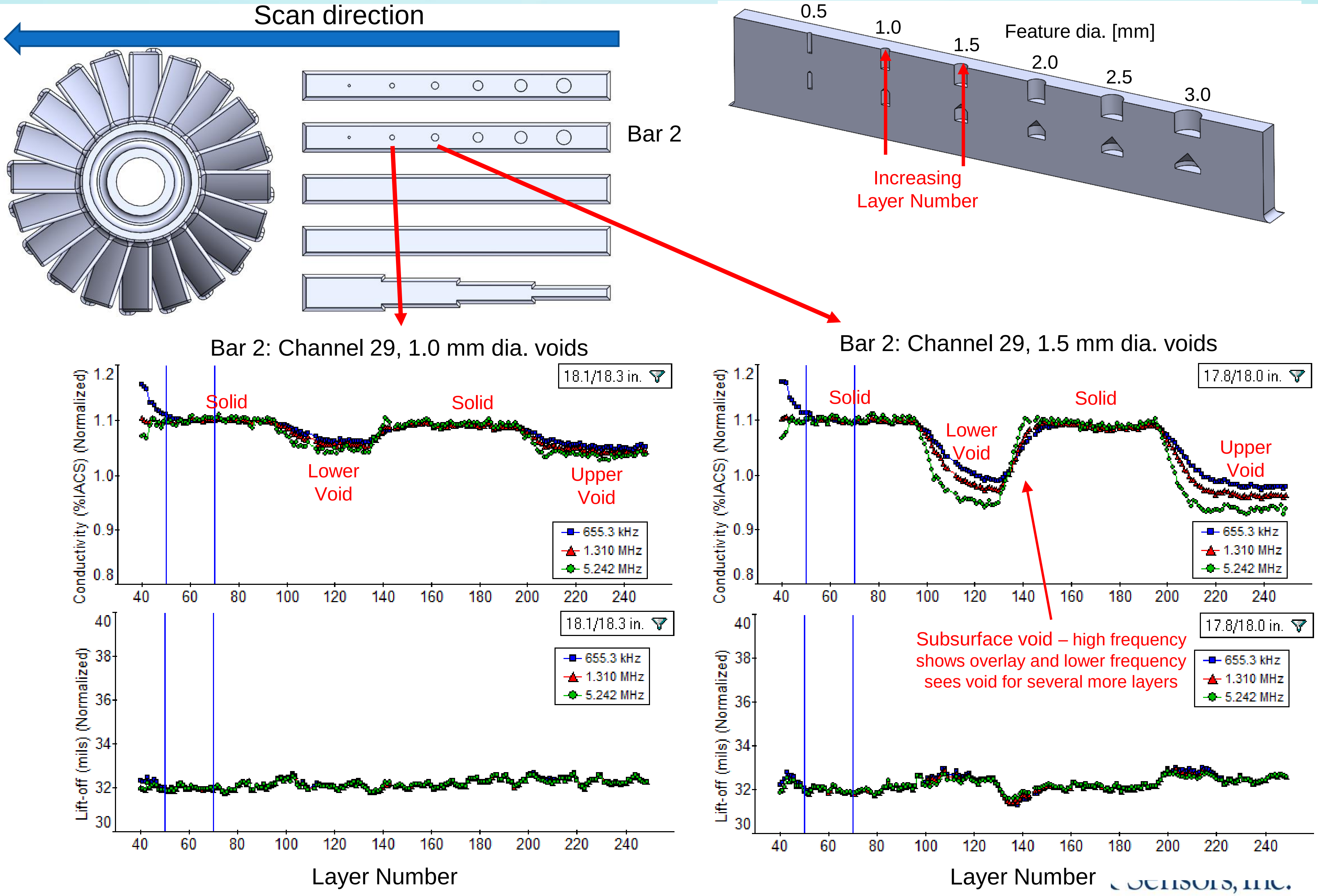
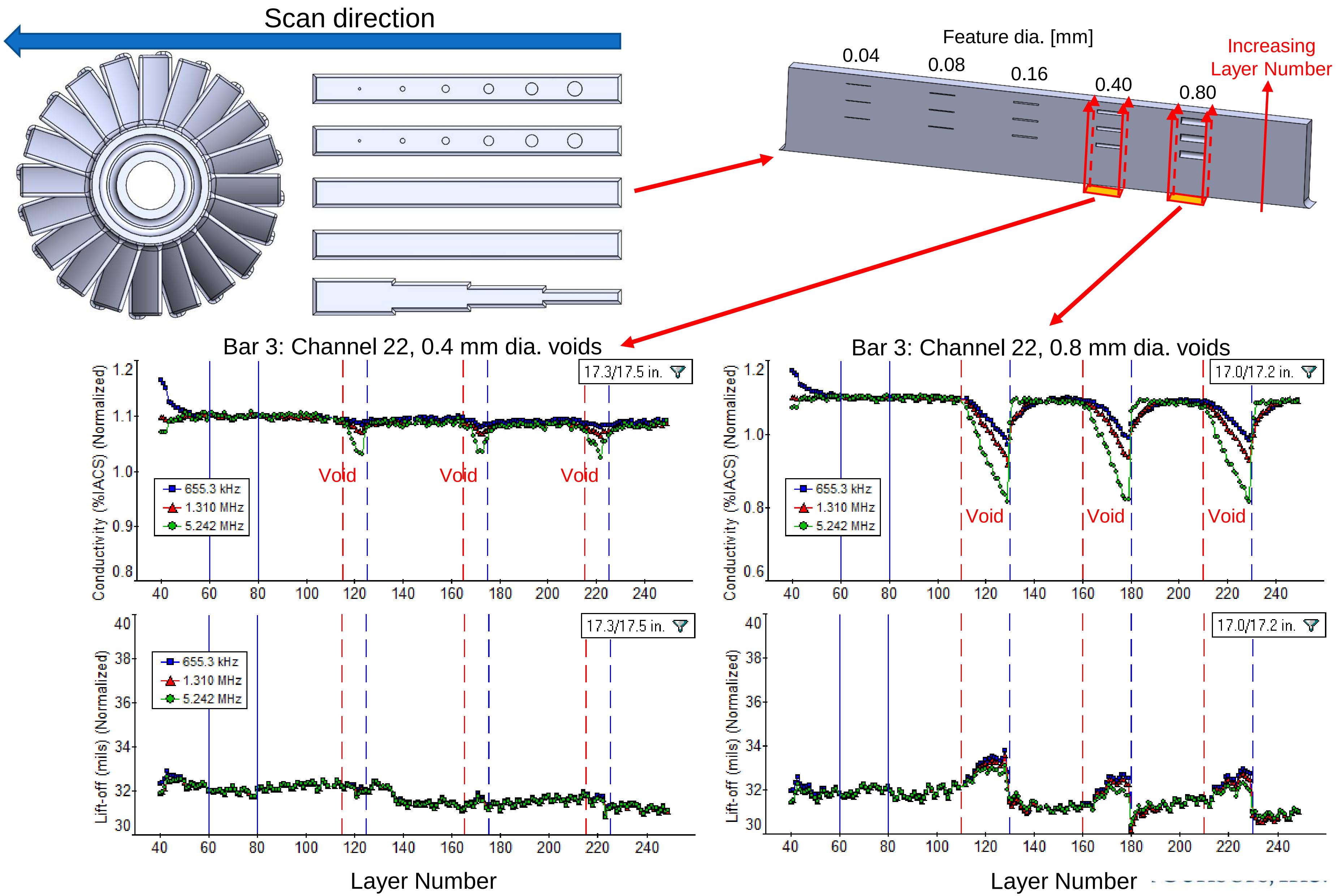
UDRI DART 2 Results (5)

- Example B-scan plots for z-direction (build direction)
  - Takes advantage of very high spatial resolution in layer direction
  - Property plots vs layer number for local regions
  - Decrease in effective (average) conductivity due to voids being present
  - Variations in lift-off can indicate void presence but also reflect surface roughness of solid material
  - Effective conductivity variation with frequency indicates subsurface void



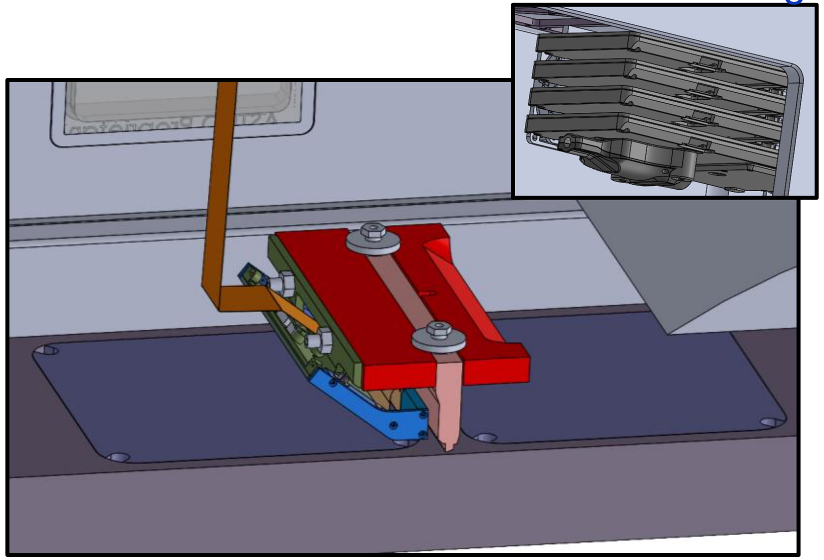
UDRI DART 2 Results (6)

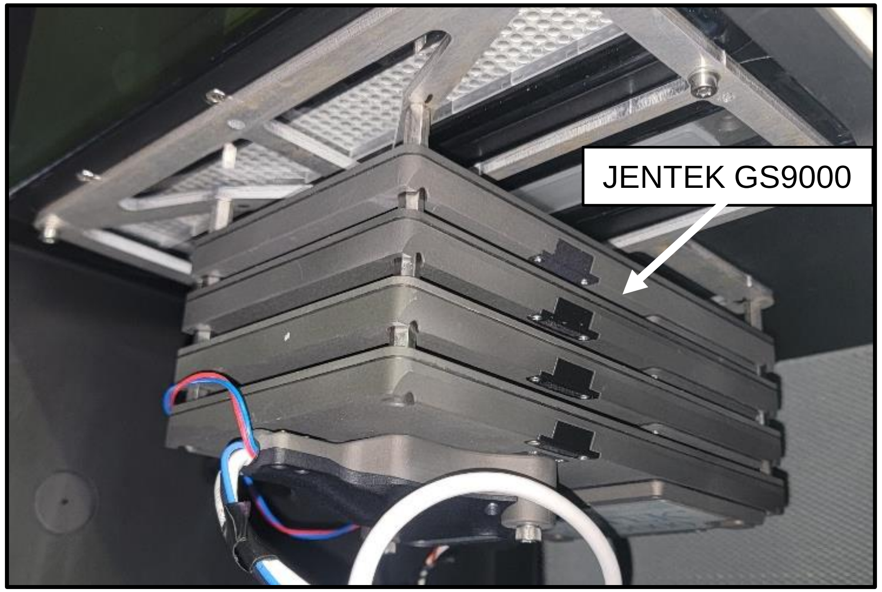
- More B-scan plots for z-direction (build direction)
  - Consistent response changes to void conditions
  - Smaller void features show same behavior as larger features
  - High frequency response changes the most for surface breaking voids
  - High frequency response returns to nominal quickly as voids are covered
  - Effective conductivity variation with frequency indicates subsurface void

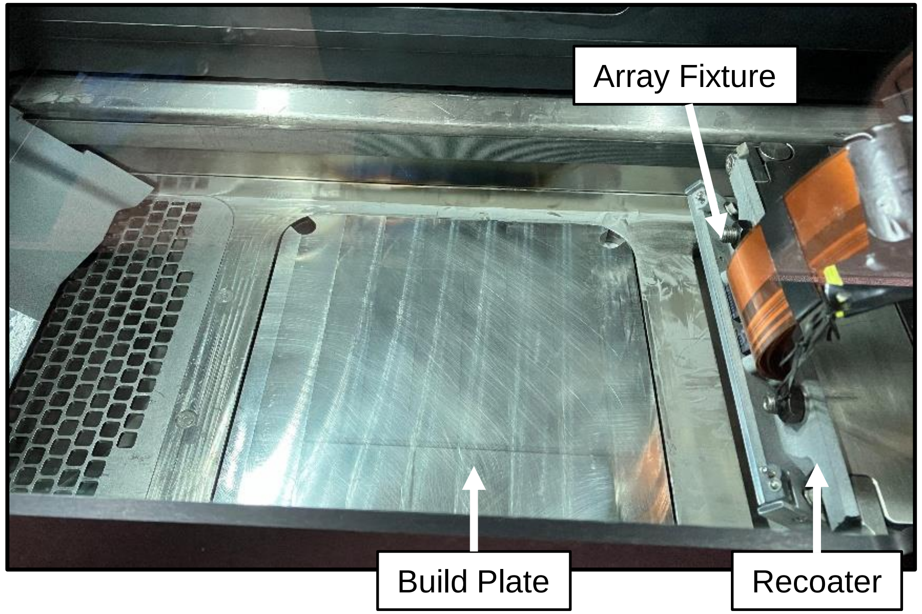


GE M2 Series 5 Configuration

Part of ASTRO-INSPIRE-ASTM In-Situ Awareness Challenge







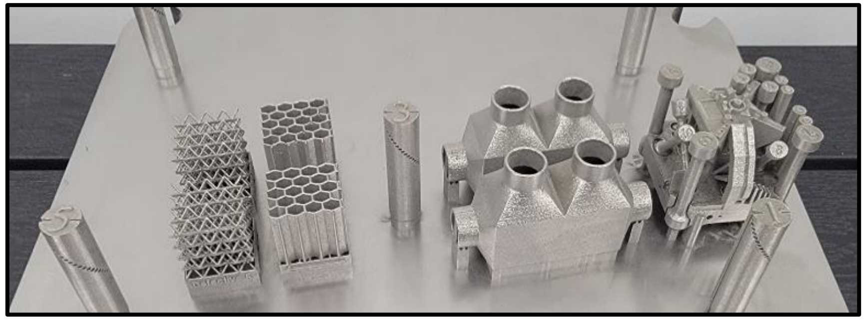
GE M2 Series 5 Build Details

- Scan speed: 55 mm/sec [1.9 in./sec]
  - did NOT alter standard motion rate
- Data Rate: ~ 0.043 mm [0.0017 in.]
  - Increments in scan direction
- Frequencies: 0.655, 1.31, 5.24 MHz
- Sensor array: FA384 MWM-Array
  - 79 sense elements
  - Channel direction size = 1.11 mm [0.044 in.]
  - Recoat direction size = 1.02 mm [0.040 in.]
  - Scan width of MWM-Array: 80.6 mm [3.17 in.]
- Air calibration
  - Performed with sensor array in air at start of build
  - Can recalibrate for each layer/scan
- Build details:
  - Material: nickel alloy 718
  - Layer Thickness: 50 microns
  - Build plate size (for GE M2 Series 5): 250 mm x 250 mm [9.84 in. x 9.84 in.]

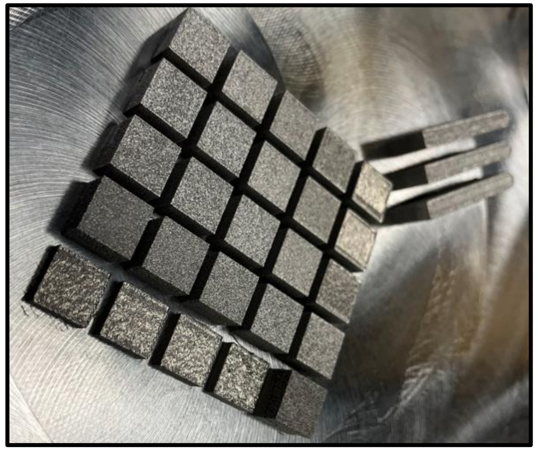
- Build 1
  - Geometric imaging and void detection
  - 250 layers
  - 5 GB data
- Build 2
  - Geometric imaging and defect detection
  - 930 layers
  - 20.4 GB data
- Build 3
  - Conductivity mapping (for quality assessment) and small void detection
  - 132 layers
  - 2.2 GB data

Build 1

Build 2



Build 3



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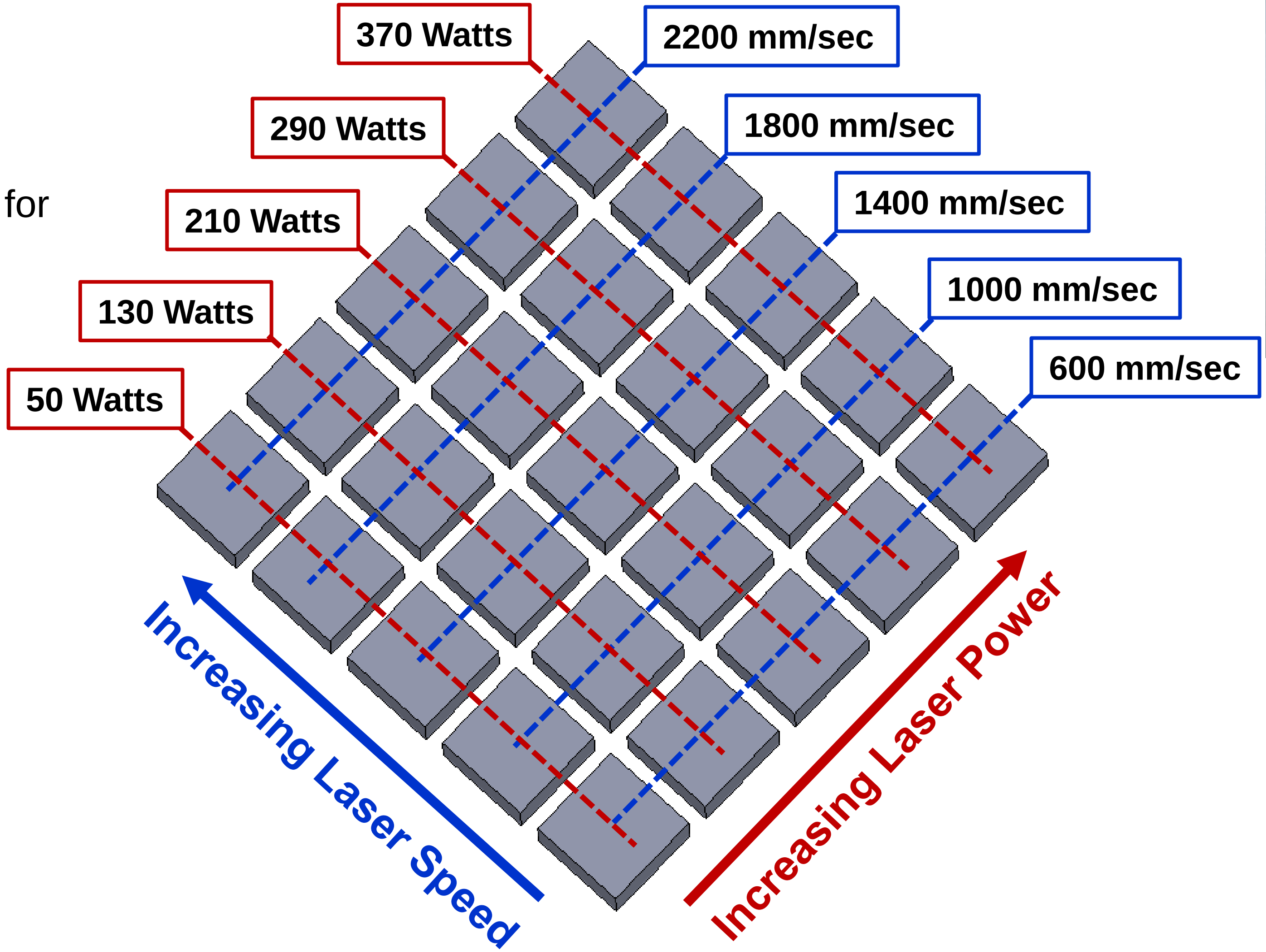
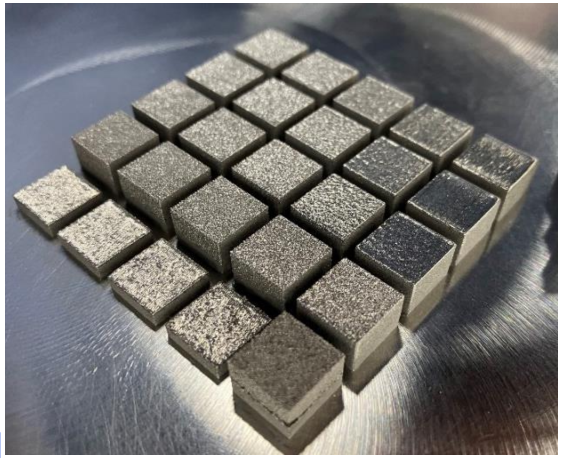
GE M2 Series 5, Build 3 Results (1)

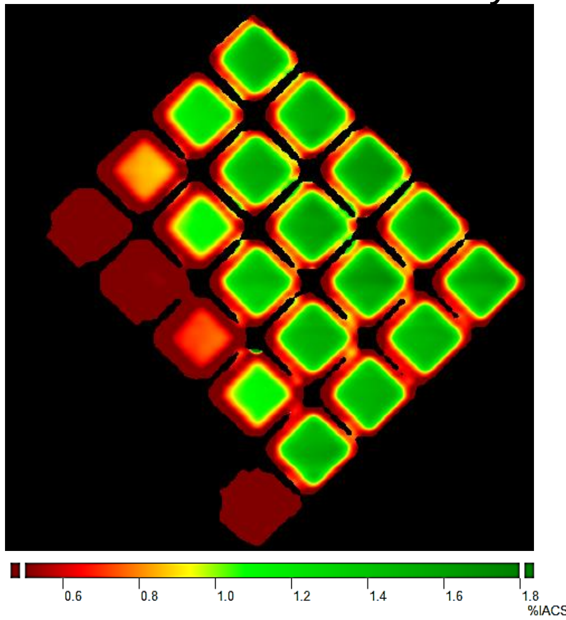
- Build 3: Conductivity Mapping (Varied Power and Speed)
- Measured conductivity correlates with processing conditions
- Can threshold conductivity for good/bad assessment
- Some pillars did not form during the build process



Photo



Measured Conductivity



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GE M2 Series 5, Build 3 Results (2)

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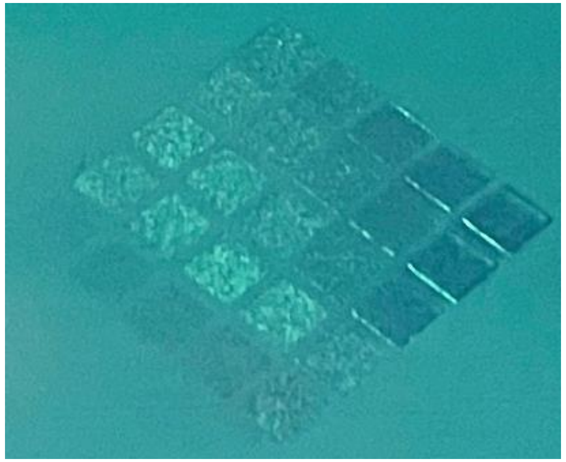
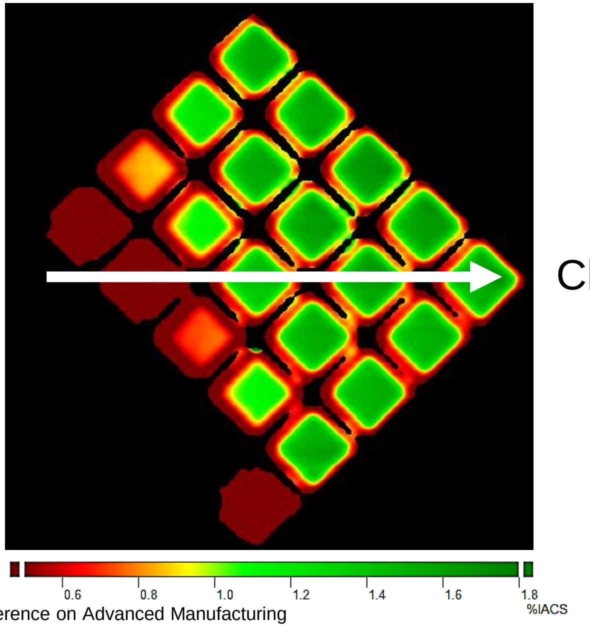
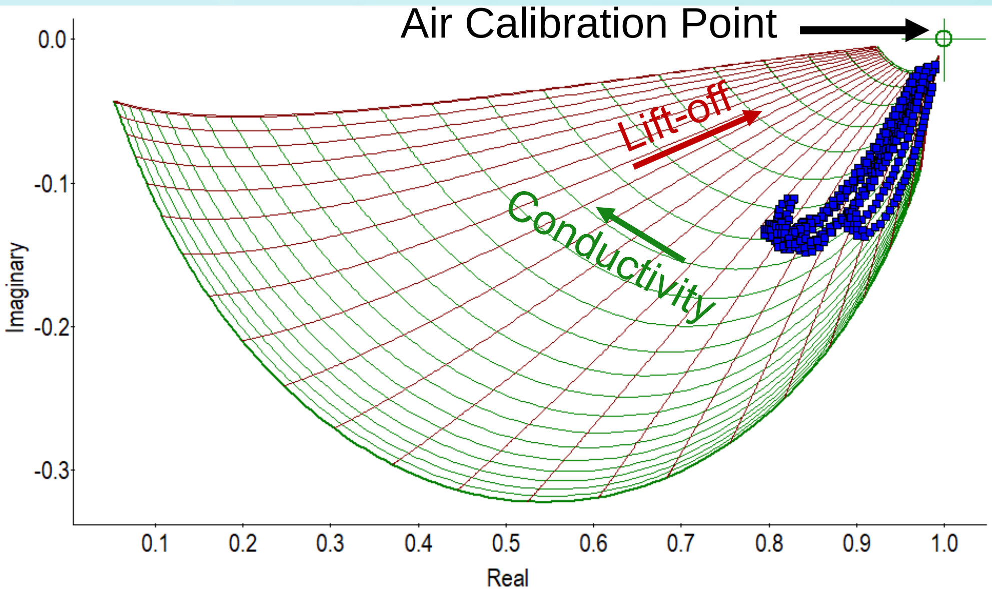
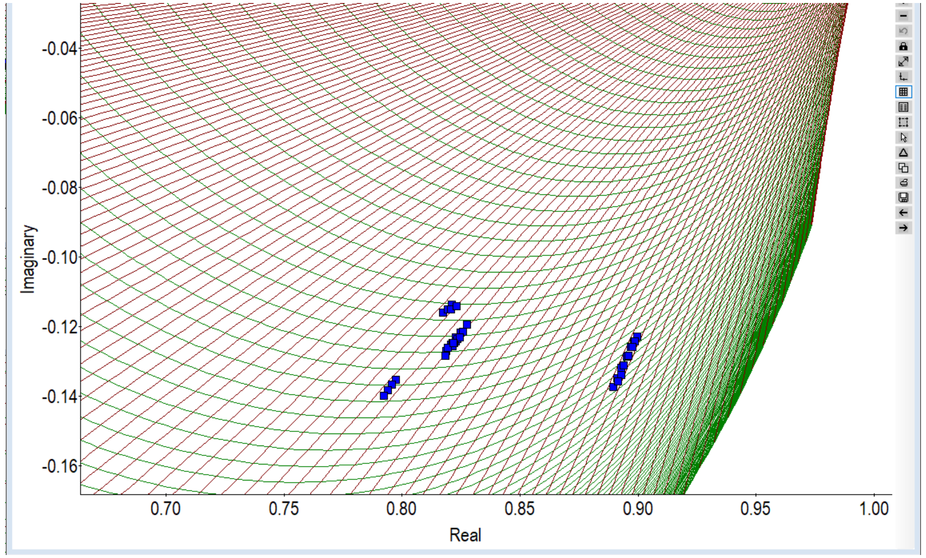
- Build 3: “Air Calibration” & Layer-by-Layer verification
- Air calibration performed prior to build
  - per ASTM E2338 and E2884
- Rapid conductivity / lift-off estimation (currently < 4 seconds per layer)
- Conductivity correlates with metallurgical properties and porosity
- Example grid display view shows lift-off conductivity and lift-off variations associated within and between each pillar





Ch 39





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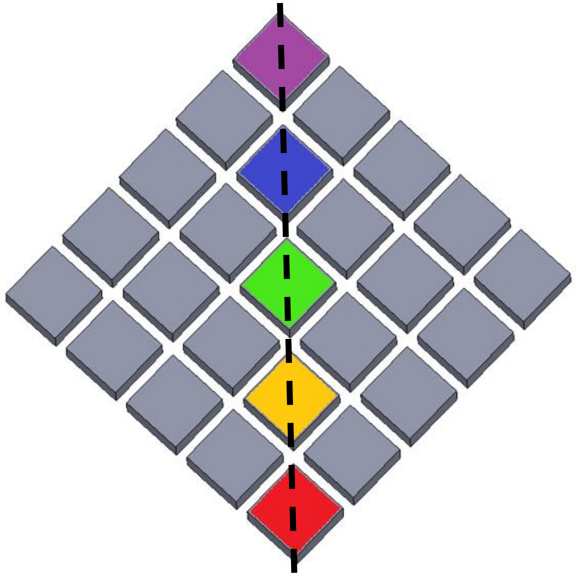
GE M2 Series 5, Build 3 Results (3)

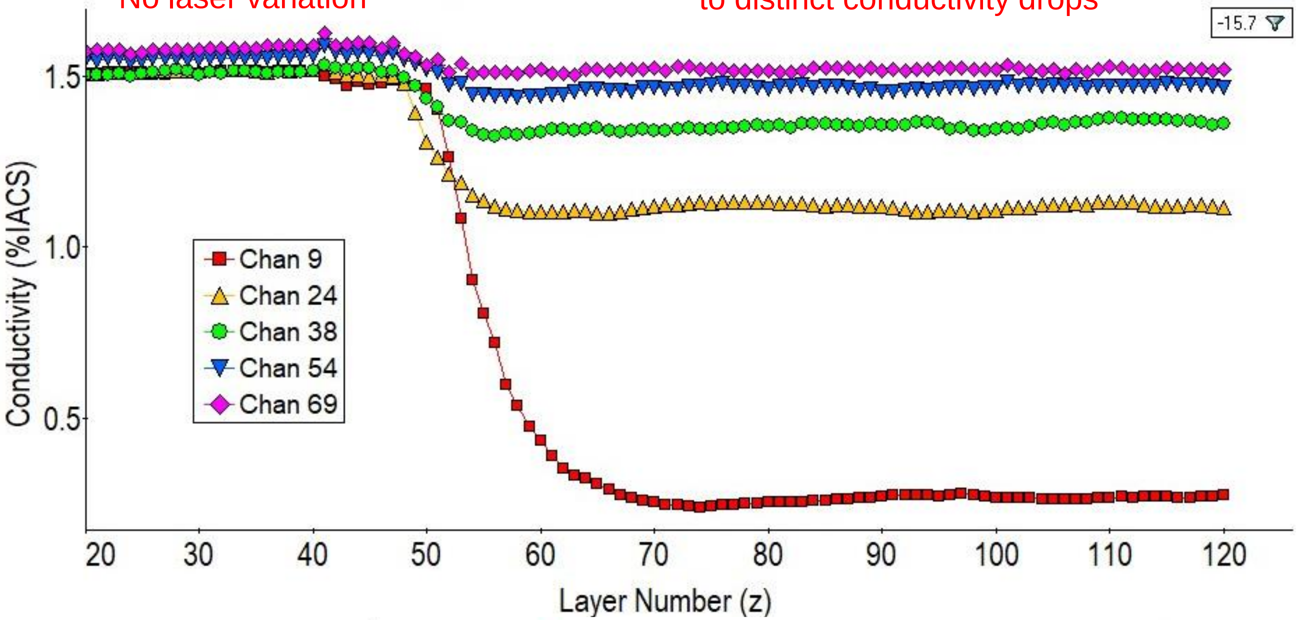
- Build 3: Conductivity Variation with Laser Parameters
- Measured conductivity correlates with processing conditions
- Provides potential for control (repair) operations and assessment of overlapping in multiple laser systems



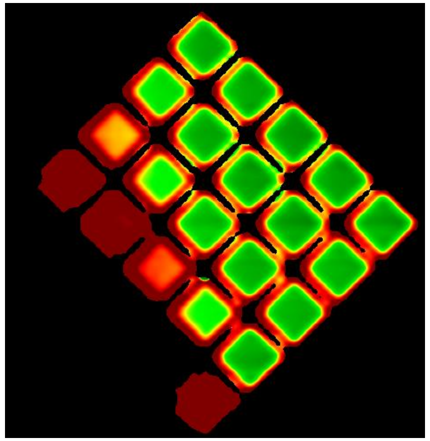
-15.7 in.
Encoder position

Support Structure
No laser variation

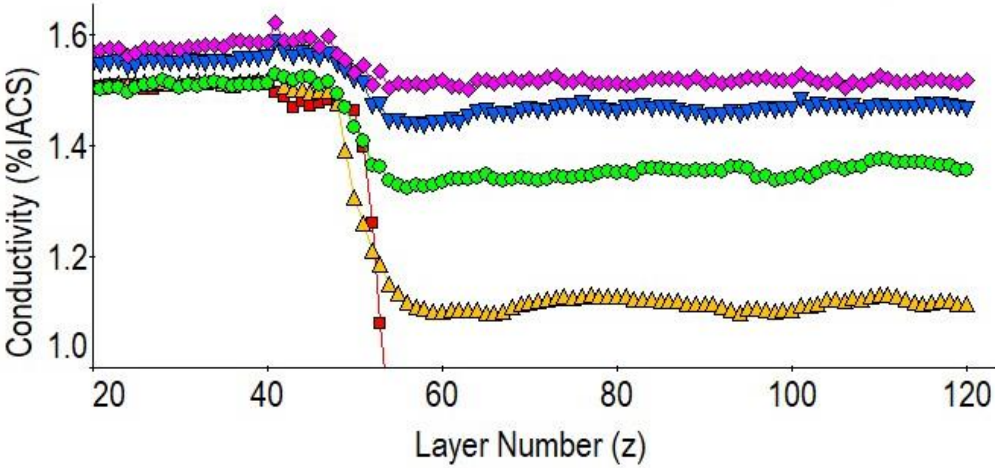
Different laser parameters lead to distinct conductivity drops



Measured Conductivity



- Channel 9 – 50 Watts; 600 mm / sec; **0.27%IACS**
- Channel 24 – 130 Watts; 1000 mm / sec; **1.12%IACS**
- Channel 38 – 210 Watts; 1400 mm / sec; **1.35%IACS**
- Channel 54 – 290 Watts; 1800 mm / sec; **1.46%IACS**
- Channel 69 – 370 Watts; 2200 mm / sec; **1.51%IACS**



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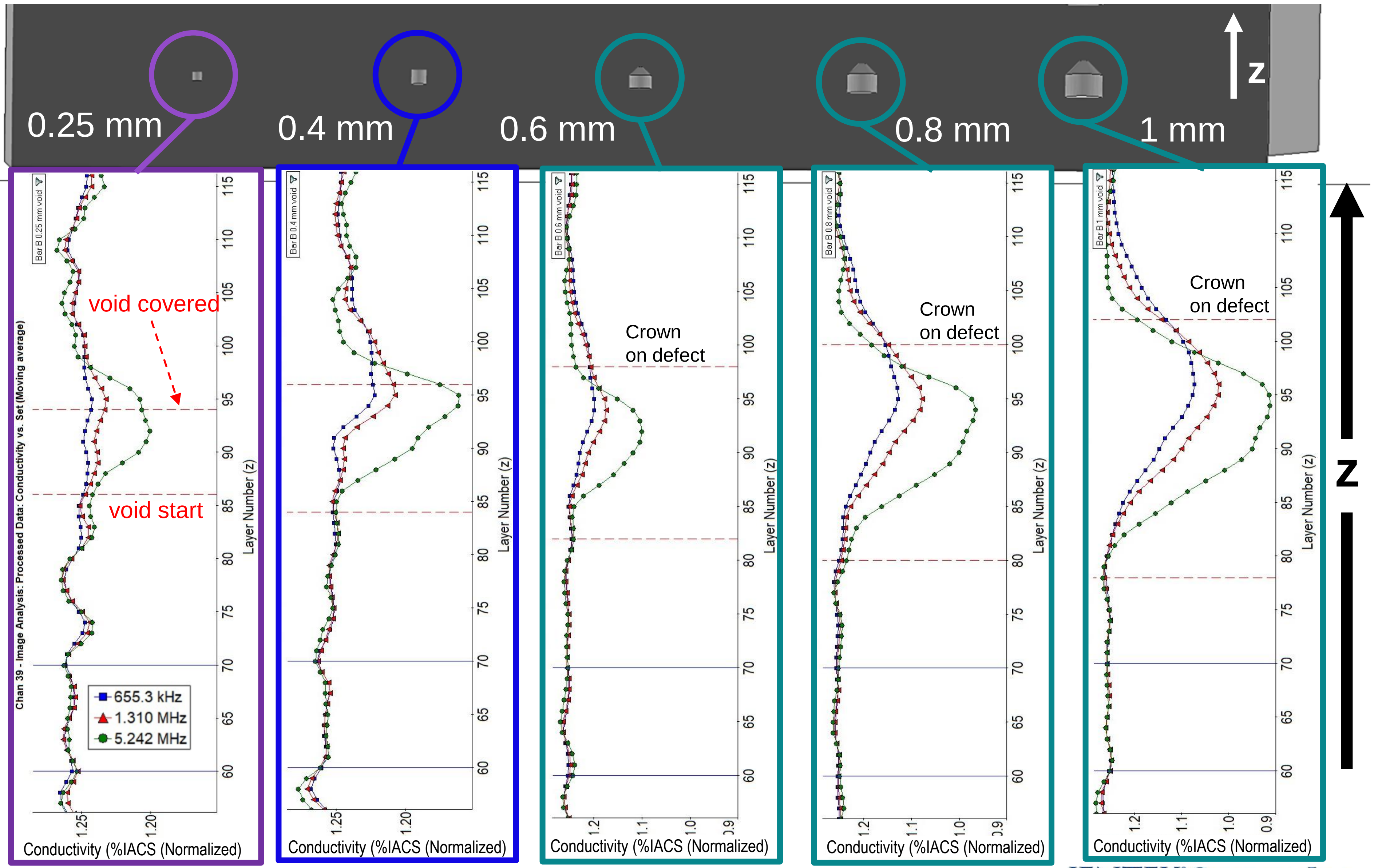
GE M2 Series 5, Build 3 Results (4)

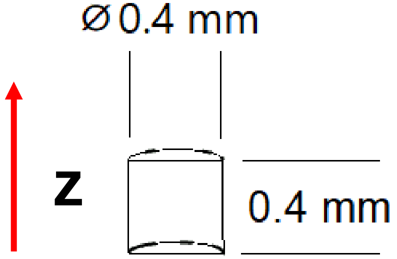
- Build 3: Local Defect Detection
- Local conductivity versus layer number (z-directed visualization)
- Indicates sensitivity to surface and subsurface (covered) defect conditions
- Measured conductivity correlates with processing conditions
- Provides potential for replacement of post-fabrication CT
  - Detection sensitivity to 0.25 mm dia. voids



2pt z-direction moving average applied to this data

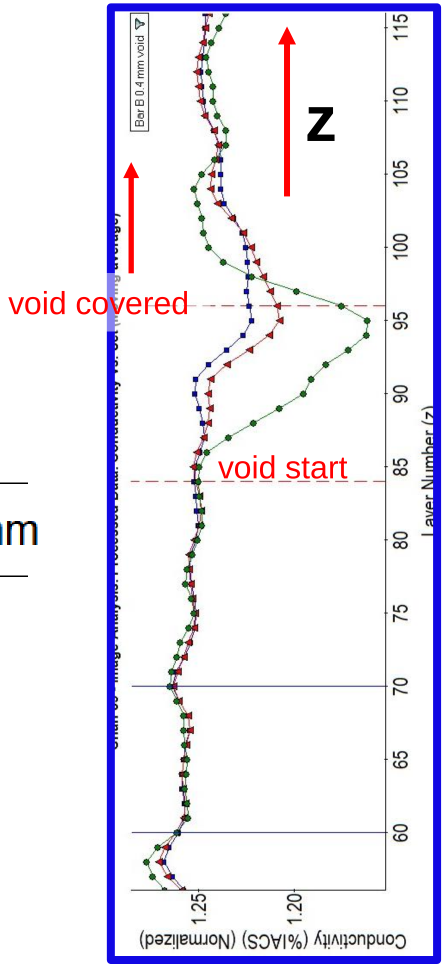
GE M2 Series 5, Build 3 Results (5)

- Build 3: Covered Void Detection
- Unique capability to detect covered defects 4-10 layers below current processing layer for these alloys
- Consistent results between UDRI DART 2 and GE M2

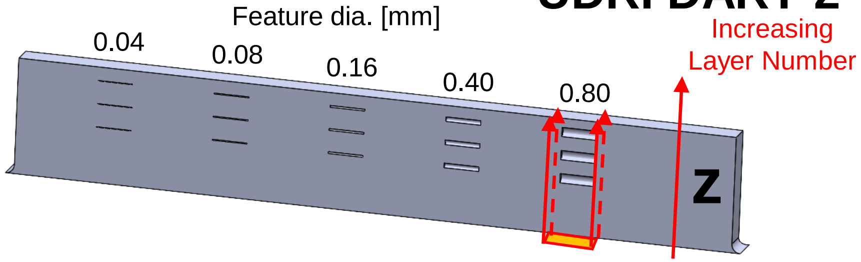


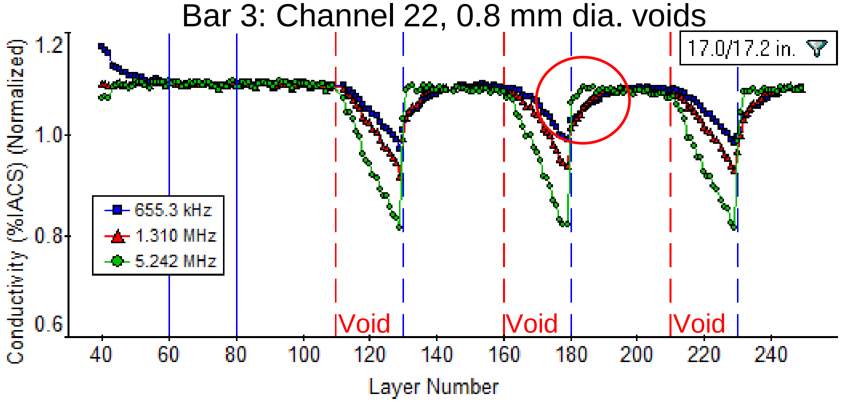
GE M2 Series 5

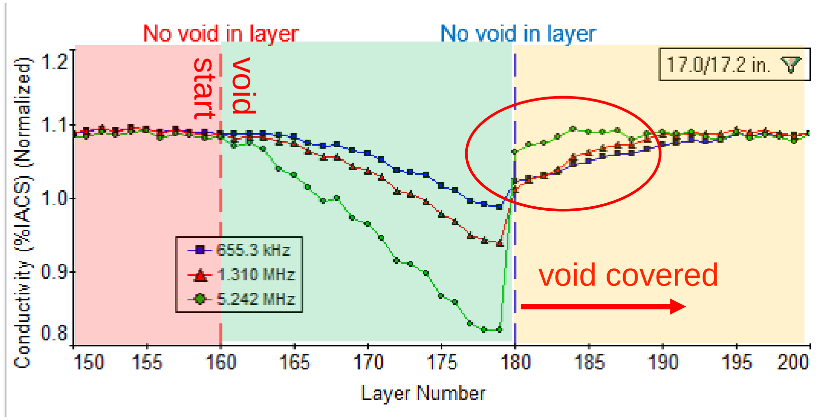
0.4 mm dia. void



UDRI DART 2







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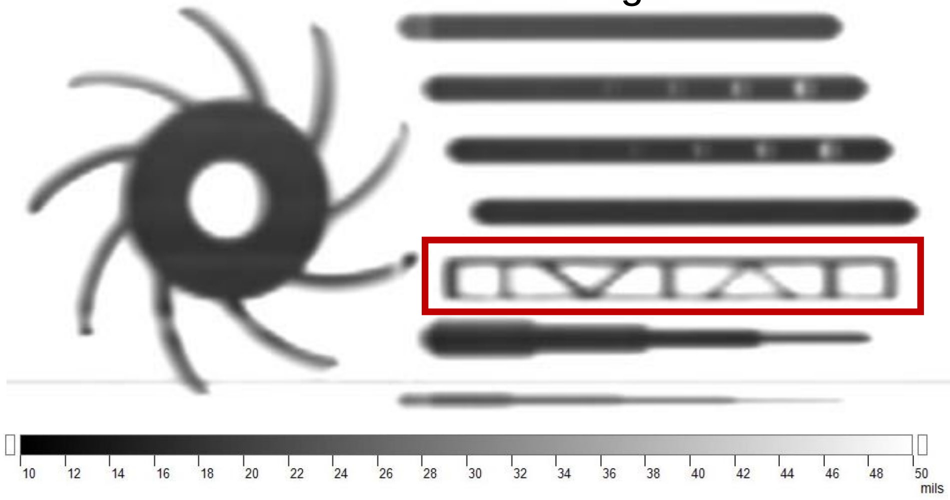
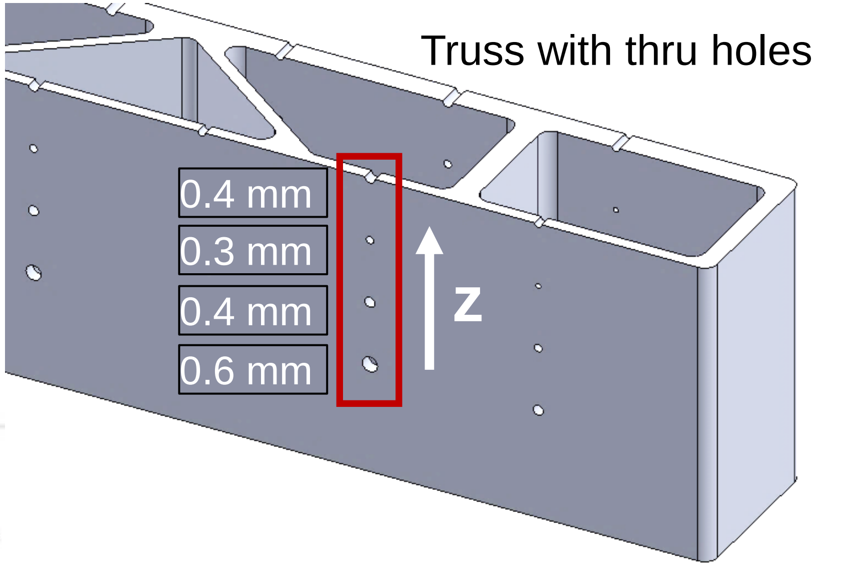
GE M2 Series 5, Build 1 Results (1)

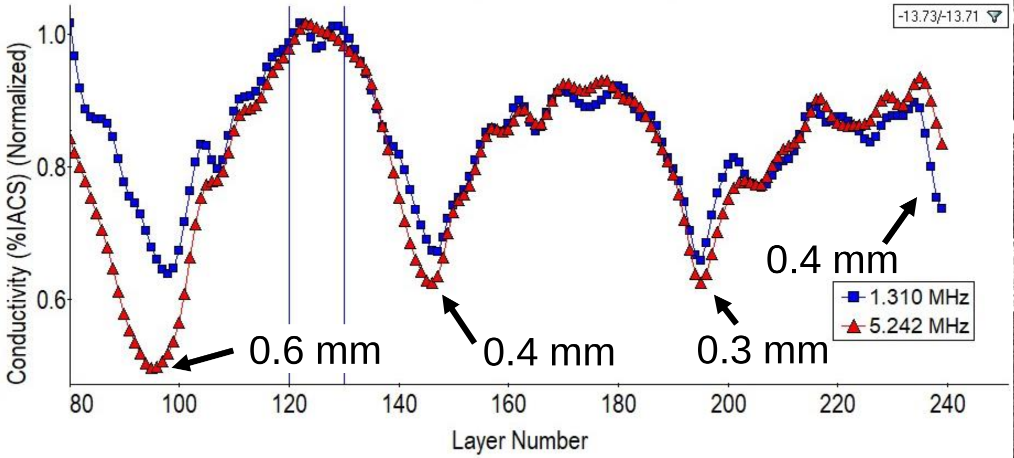
- Build 1: Void Detection in Thin Walls
- Each void (thru hole) appears as local reduction in effective conductivity
- z-directed filtering not yet applied to this data yet
  - Anticipate training / machine learning approach

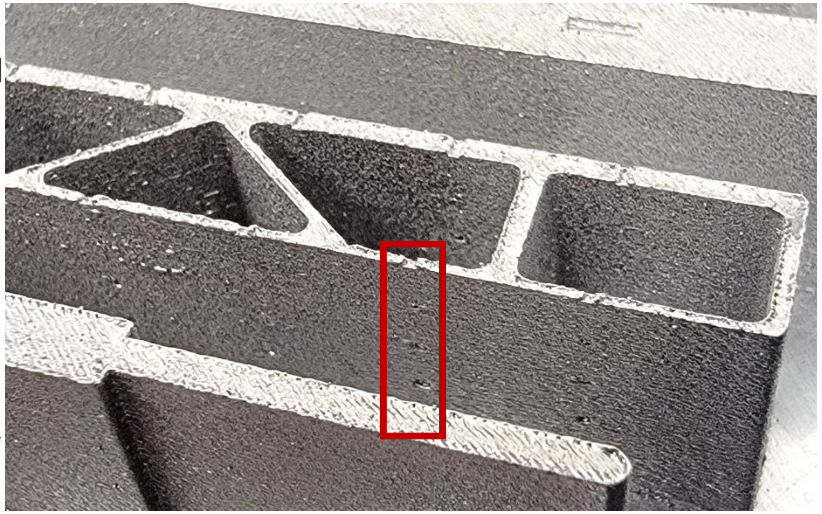
Effective Lift-off Image





Conductivity vs. Layer # (z)



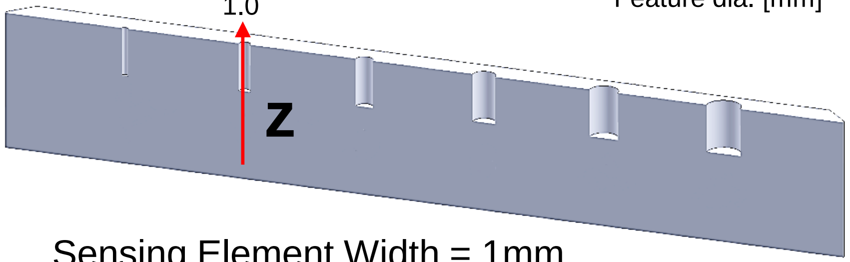


GE M2 Series 5, Build 1 Results (2)

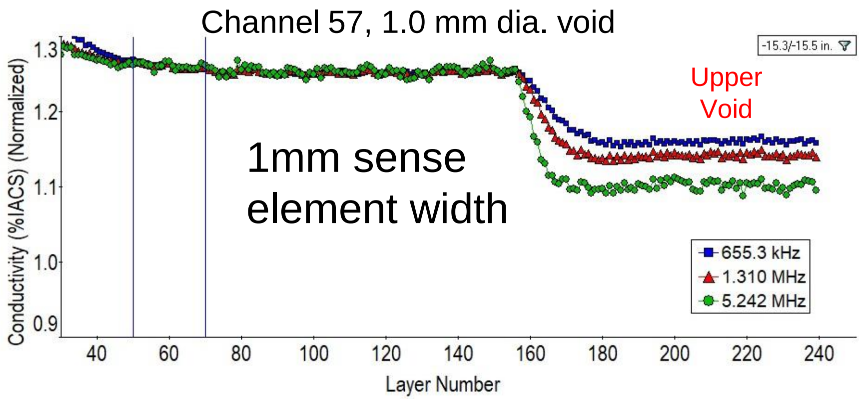
- Build 1: Void Detection
- Consistent results between UDRI DART 2 and GE M2
- Surface breaking voids appear primarily as local reduction in effective conductivity, with ~constant lift-off
- Smaller sense elements provide greater spatial resolution and larger effective conductivity change for the voids

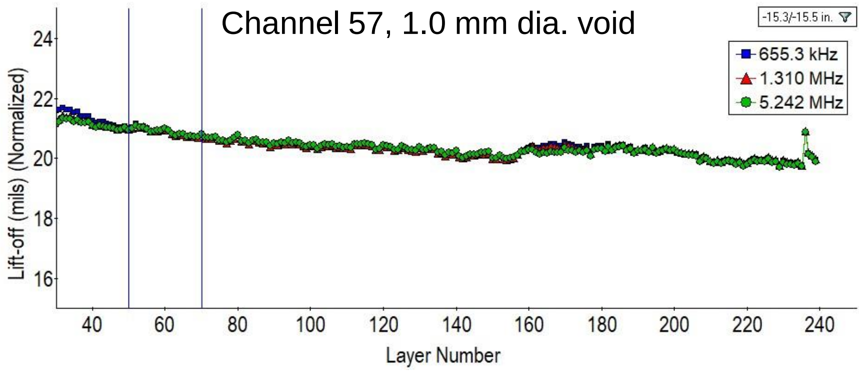
Build 1: GE M2 Series 5

Feature dia. [mm]



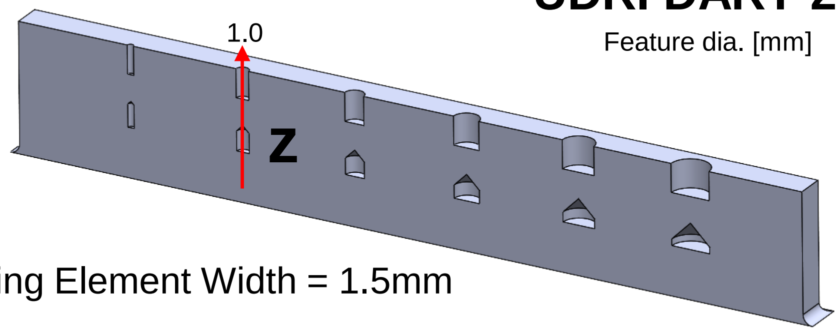
Sensing Element Width = 1mm



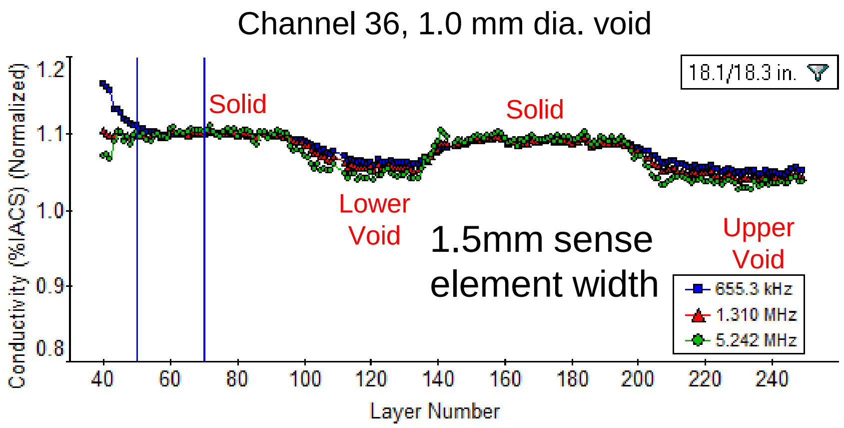


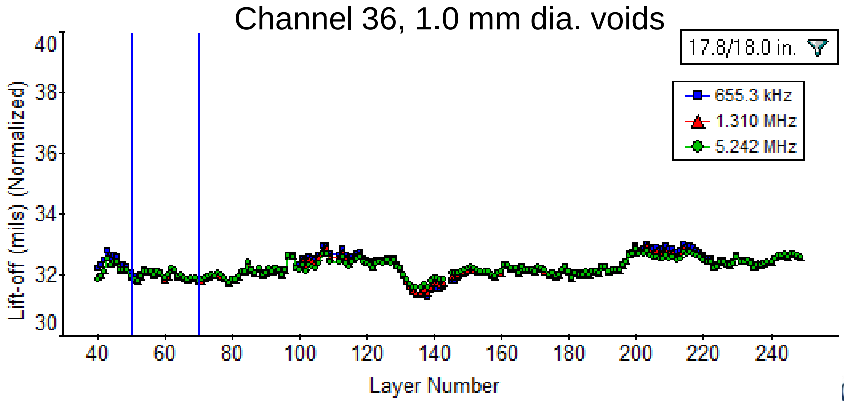
UDRI DART 2

Feature dia. [mm]



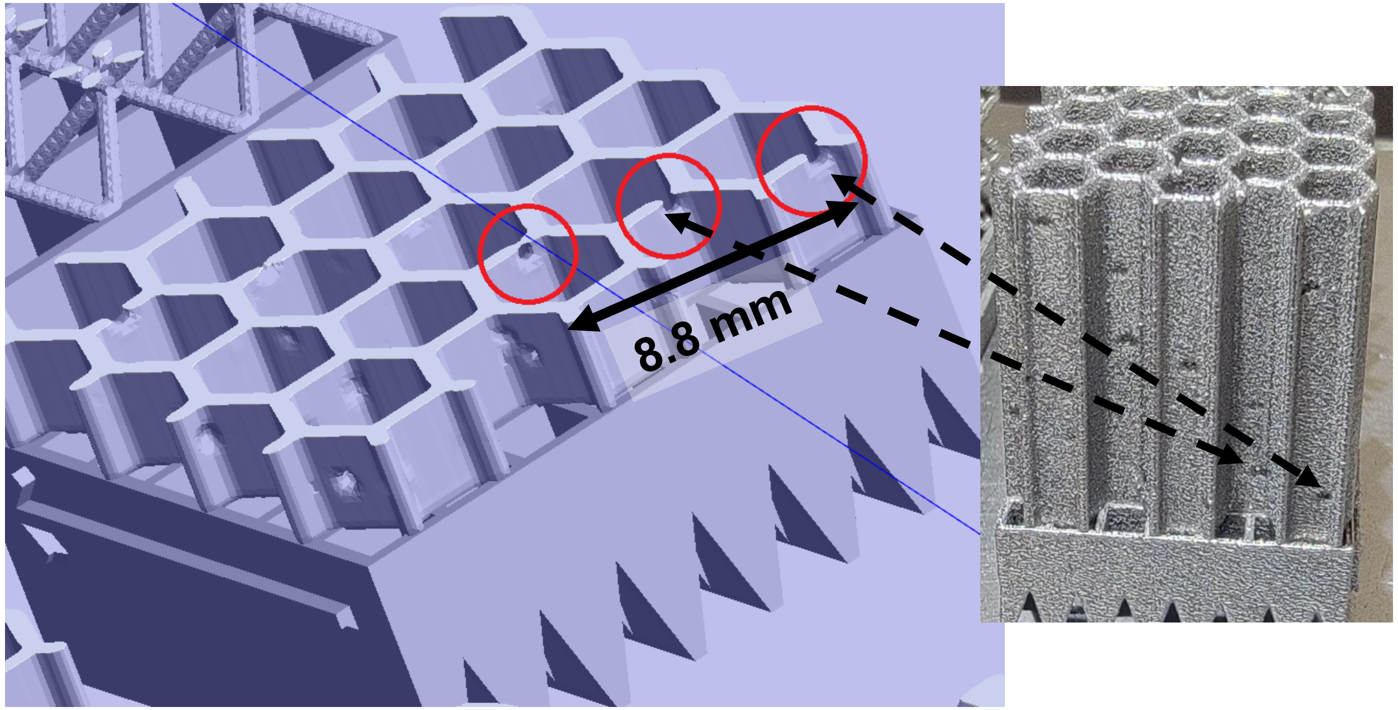
Sensing Element Width = 1.5mm

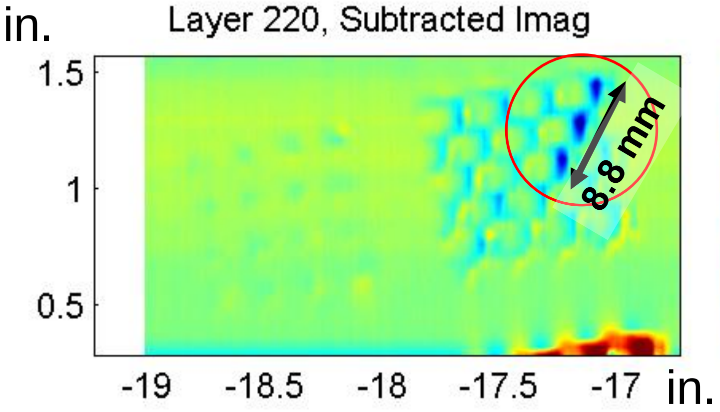


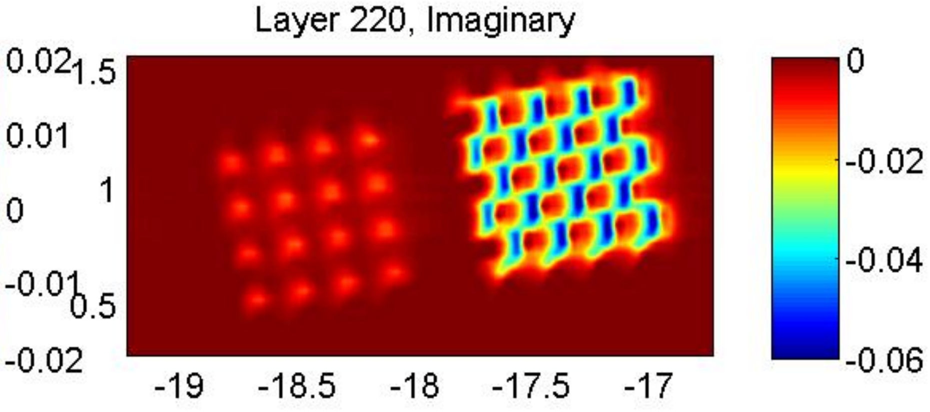


GE M2 Series 5, Build 2 Results (1)

- Hex Structure Example
- Wall thickness: ~0.6mm
- Defects: 0.35mm, 0.5mm, 0.55mm thru wall
  - surface breaking and subsurface voids
- 1.3 MHz data with image subtraction shows benefit of spatially consistent data and simple processing
- Analyzed raw data since property estimates limited by thin walls
- z-directed filtering not yet applied – requires training on representative defects







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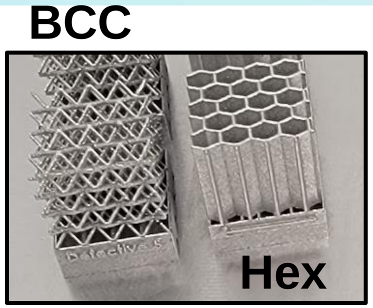
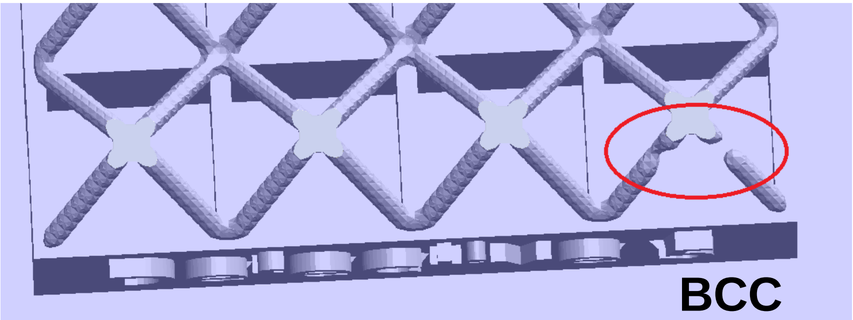
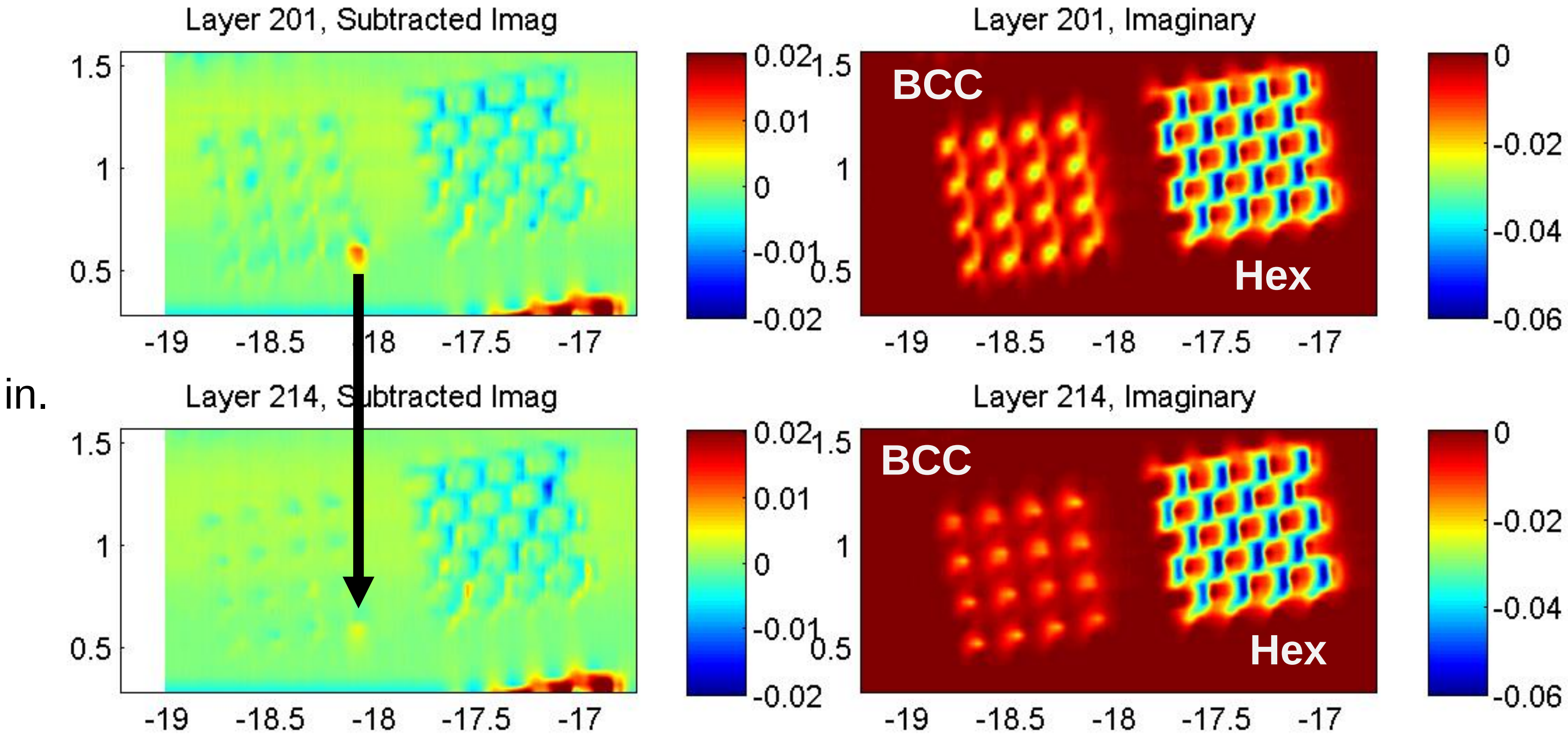
GE M2 Series 5, Build 2 Results (2)

- BCC Structure Example
- Thin geometric features
- Defects appear as incomplete/missing features
- Simple image subtraction shows flaws consistent with expected defect location
- Analyzed raw data since property estimates limited by thin material conditions
- z-directed filtering not yet applied – requires training on representative defects and ability to follow build contours

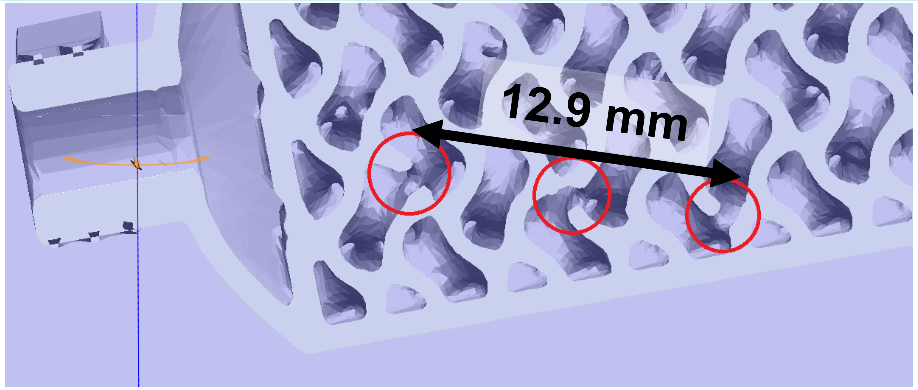


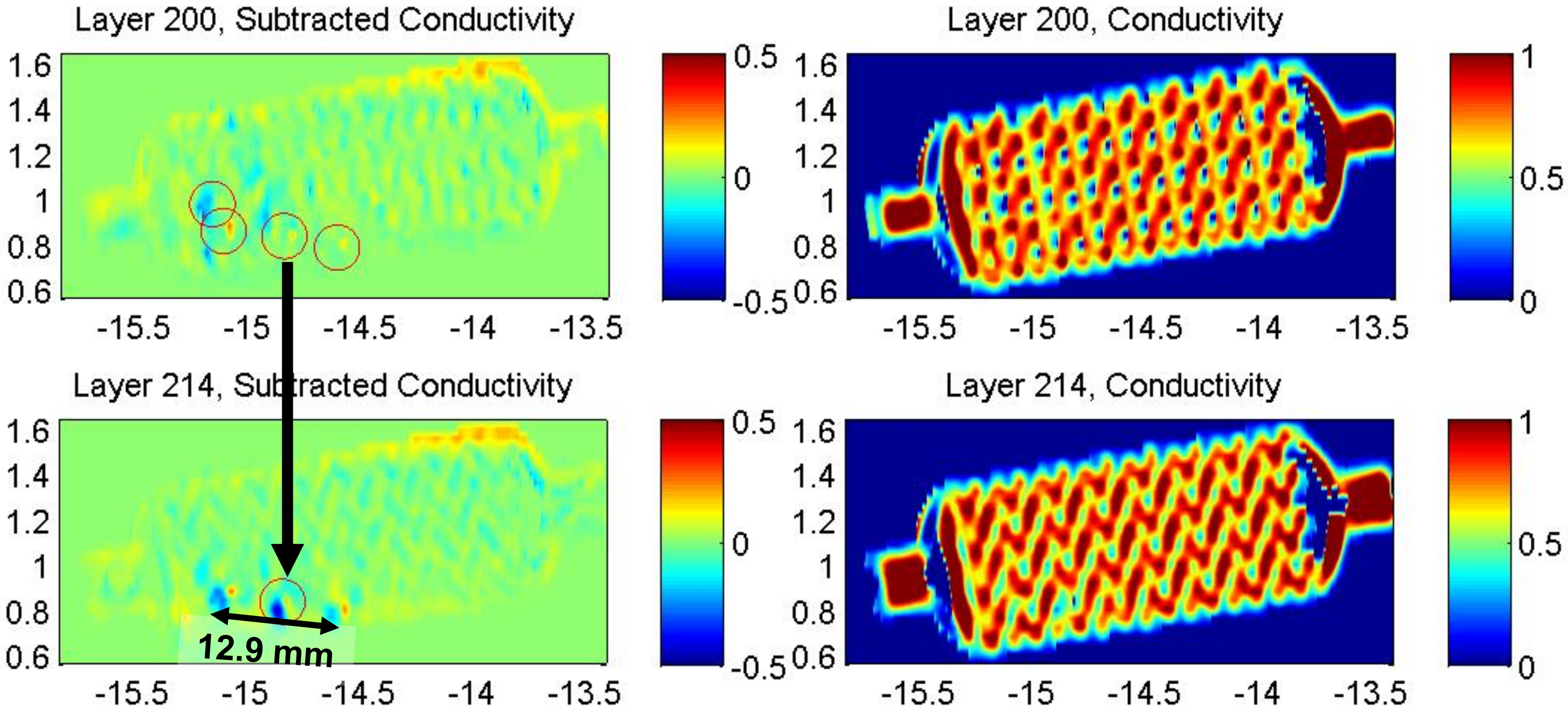




GE M2 Series 5, Build 2 Results (3)

- Heat Exchanger Example
- Thin walls with varying directions
- Defects appear as missing material
- Simple image subtraction shows flaws consistent with expected defect location
- Analyzed property data since sufficient material within sensor footprint to obtain consistent property values
- z-directed filtering not yet applied – requires training on representative defects





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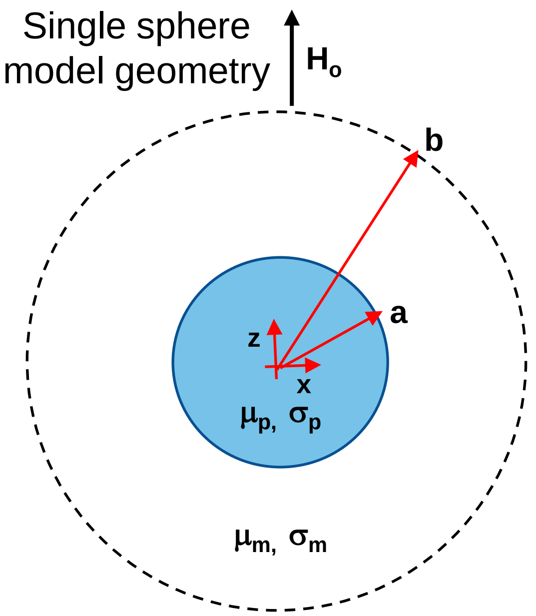
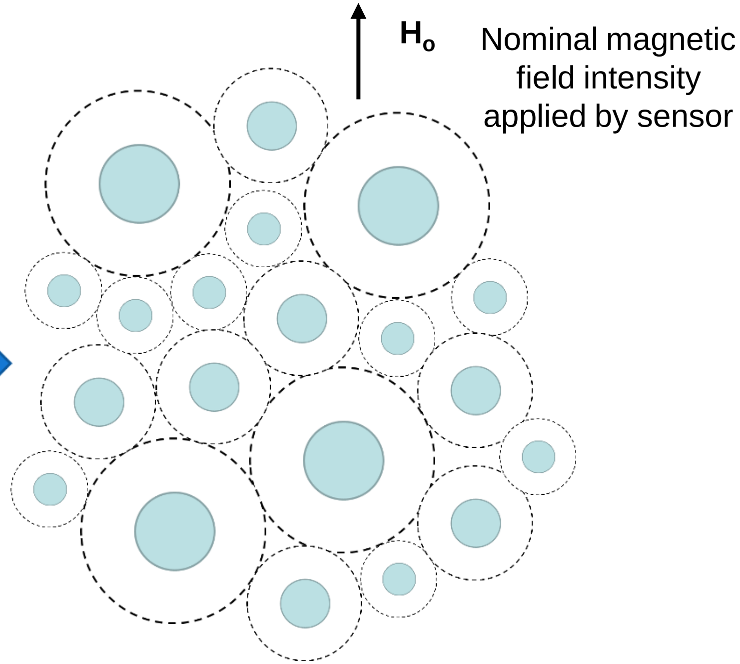
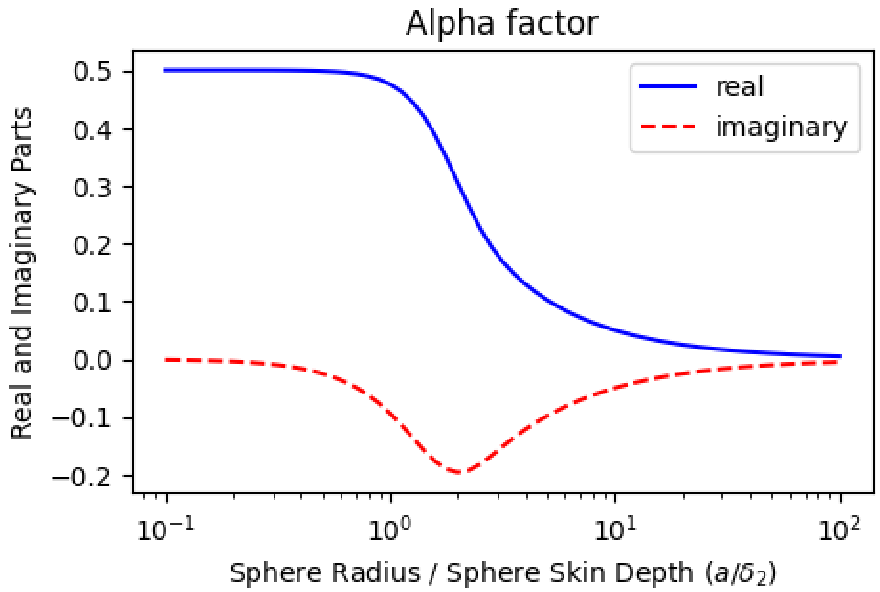
Powder Model (1)

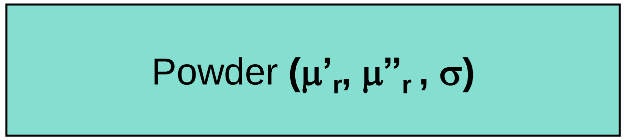
- Unpublished eddy current particle model developed for magnetic and/or conducting powders
- Eddy current effects incorporated into composite sphere assemblage model
- Spans low frequency (no eddy currents) to high frequency (thin skin depth compared to particle diameter) regimes
- Alpha factor indicates contribution of eddy currents to effective permeability of powder
- Critical frequency is when the sphere radius is two skin depths for the powder material







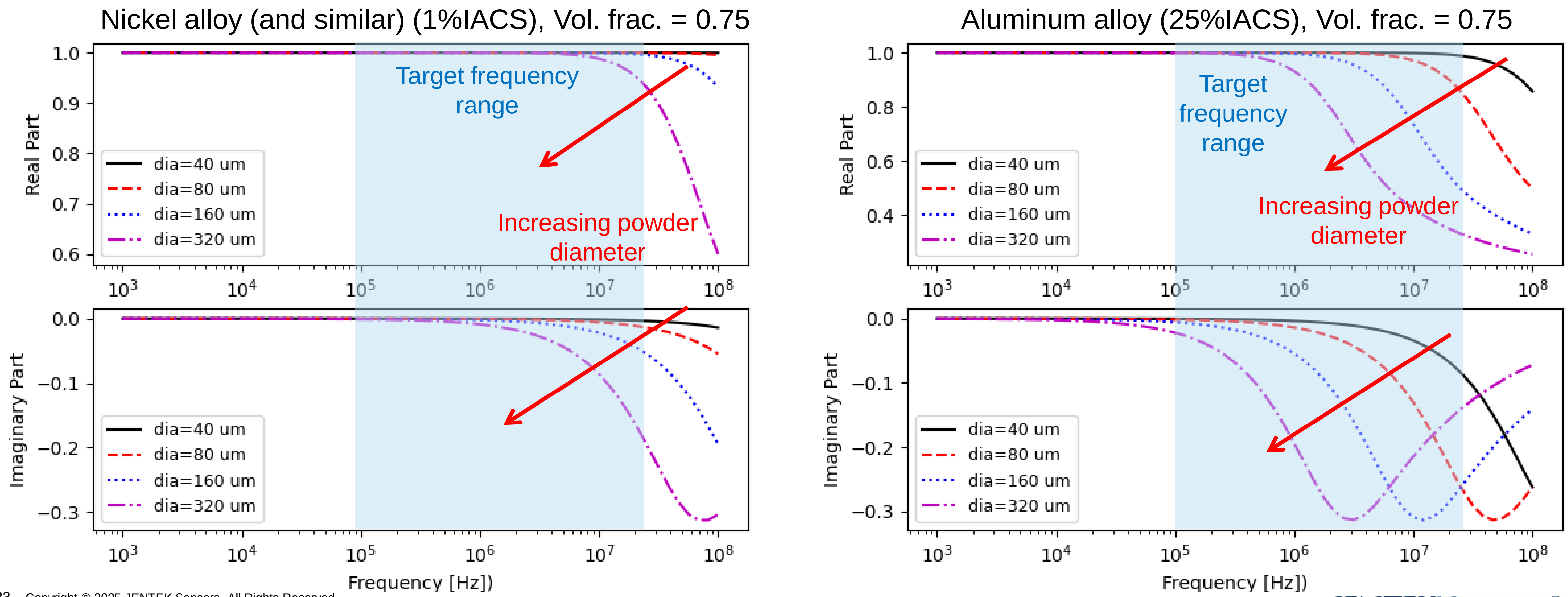
Layered Media Geometry



Powder diameter, conductivity, and volume fraction represented as real and imaginary parts of relative permeability

Powder Model (2)

- Representative results for low and moderate conductivity, nonmagnetic powders
- Powder response like ‘air’ unless skin depth is comparable to the powder radius



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Summary

- Eddy current methods can provide complementary in-situ inspection information during the build process
  - Minor system modifications do not affect build conditions (build speed or part condition)
- Local defect detection capability
  - Potential replacement for post-production CT for part qualification
- Subsurface defect and conductivity (metallurgical) condition assessment
  - Not available from other in-situ methods
  - E.g., overlap properties from laser stitching
- Sub-pixel geometric imaging for edges and small features
  - Longer term development
  - Likely requires fusion with optical or IR methods
- Rapid processing can enable subsequent layer feedback control
  - Potential to modify build parameters to repair defect conditions
- Eddy current arrays suitable for other advanced manufacturing approaches:
  - PBF
  - DED and AFSD
  - Cold spray and other coatings
  - Advanced welding
- Future work:
  - Continued refinement of analytical methods
  - Support for wider eddy current arrays
  - More support data fusion analytics

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Thank you.

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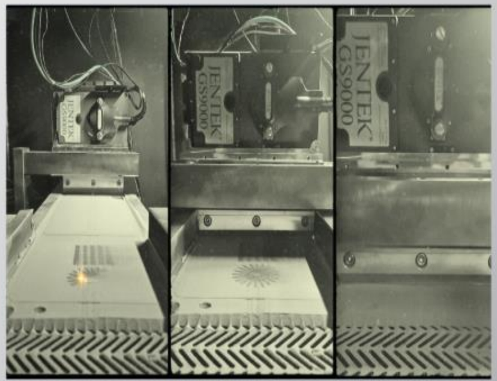
IN-PROCESS, NON-CONTACT SENSING/INSPECTION

High resolution for defects, properties and geometry.



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