6 - 9 October 2025 | Orlando, Florida

Non-Contact, In-Process ET-Array Methods for Industrial Processes

Presenter: Dr. Neil Goldfine, President & Chief Engineer [+]

Authors: N. Goldfine[+], A. Washabaugh[+], T. Dunford[+], T. Simon[+], S. Chaplan[+], M. Windoloski[+], H. Foelsche[+], N. Maleski*, J. Orr*, S. Mirmasoudi*

JENTEK Sensors, Inc. [+]

jentek@jenteksensors.com | neil.goldfineoverseas@jenteksensors.com

www.jenteksensors.com

University of Dayton Research Institute (UDRI) *

sara.mirmasoudi@udri.edu | jessica.orr@udri.udayton.edu

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Abstract

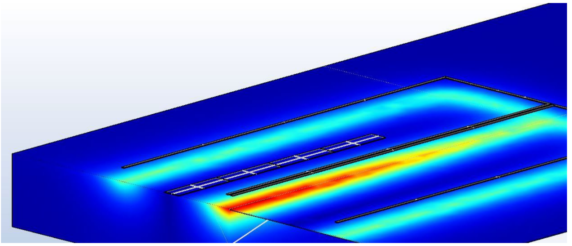
This paper describes methods for implementation of non-contact eddy current array (ET-Array) sensing for industrial processes. In-process (in-situ) sensing for Additive Manufacturing (AM) and continuous manufacturing processes (e.g., for multilayered electrode sheets) must keep up with production rates while enabling process qualification. This paper presents novel implementations of unique ET-Arrays (called MWM-Arrays) that have been continually upgraded since foundational research at MIT. This has included “air calibration”, model-based multivariate inverse methods (MIMs), intelligent filtering, fully parallel electronics, small sensing element size (down to 0.75 mm), and support for established artificial intelligence/machine learning (AI/ML) capabilities. Processes such as Laser Powder Bed Fusion (LPBF), Directed Energy Deposition (DED), and Additive Friction Stir Deposition (AFSD) require more observability than is currently available with conventional (e.g., optical) methods to overcome specification hurdles associated with critical component qualification (for processes, machines, and parts). Recent results are presented for LPBF in-situ sensing along with a description of methods and advantages of novel ET-Arrays and data analytics enhancements. A key goal for LPBF in-situ sensing is to provide an alternative to Computed Tomography (CT) as the only method for qualification. Achieving this requires reliable detection of defects approximately 0.25 mm or larger. Moreover, as AM parts increase in size and complexity, CT may no longer meet qualification requirements. Layer-by-layer in-situ ET-Array sensing has the potential to be a viable alternative to CT for component qualification. Although the majority of recent work has focused on AM, this technology also offers value for legacy and advanced processes that lack observability for defects, geometry/dimensions, and material properties.

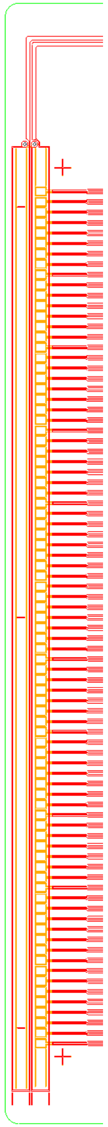
Presentation Outline

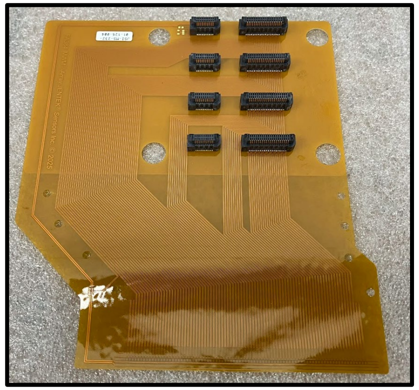
- MWM-Array Non-Contact In-Line Technology Background
- Additive Manufacturing Patents
- Laser Powder Bed Fusion (LPBF) In-Situ Sensing with MWM-Array
  - Previous and Upcoming Machine Agnostic Installations
    - EOS M 290 (Nov 2025)
    - Colibrium Additive (GE) M2 Series 5 (Aug 2025)
    - UDRI DART 2 (Feb 2025)
  - MWM-Array Technology Advantages
  - Data Interpretation
- Other Advanced Manufacturing Opportunities
  - Directed Energy Deposition (DED), Additive Friction Stir Deposition (AFSD), Cold Spray and other Coatings, Advanced Welding, EV Battery Electrodes and other continuous processing

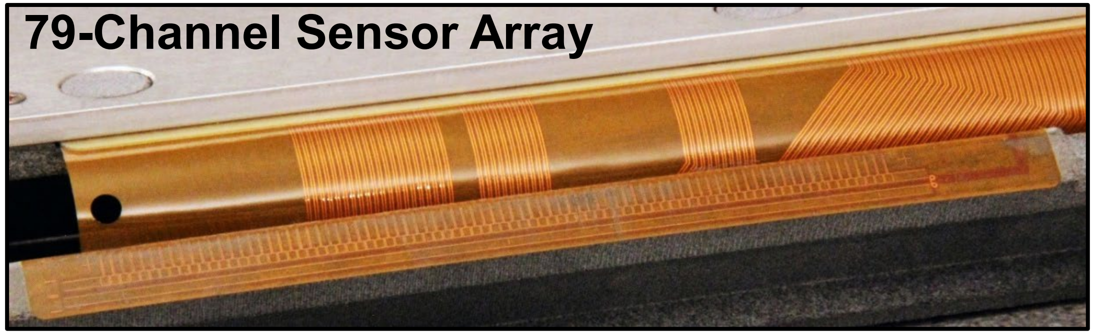
MWM-Array® Non-Contact In-Line Technology (High Level)

- All channels recorded simultaneously at three frequencies simultaneously
- Model-based multivariate rapid physics solver (conductivity and lift-off); enabling air calibration and rapid data analytics
- Automatic rescaling of conductivity response for variable lift-off
- Rapid data analytics and relatively small file sizes
  (e.g. <4 sec processing per LPBF layer; <5 GB per 250 layers)
- Patented Eddy Current Array method for LPBF and DED
  (example issued patents: 12,253,492; 11,802,851; 11,747,304;11,543,388; 11,268,931; 11,268,933; others issued and pending)
- For LPBF, there are two installation configurations:
  - Instrument on recoater
  - Instrument on build chamber wall with flex cables to sensor

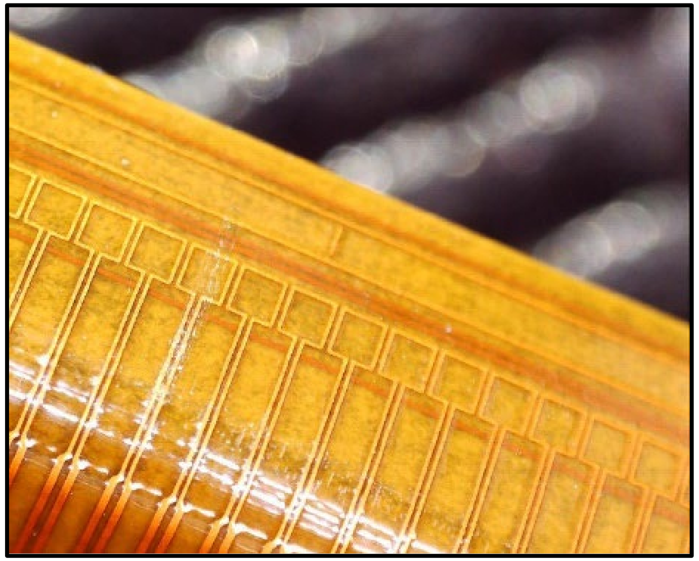








79-Channel Sensor Array



JENTEK Additive Manufacturing Patents

Issued Patents (from 2016 filing)

12,253,492 – IN-PROCESS QUALITY ASSESSMENT FOR ADDITIVE MANUFACTURING,
March 18, 2025
https://patents.google.com/patent/US12253492B2/en?oq=12253492

11,802,851 – SEGMENTED FIELD EDDY CURRENT SENSING FOR DISPERSIVE PROPERTY MEASUREMENT AND COMPLEX STRUCTURES,
October 21, 2023
https://patents.google.com/patent/US11802851B2/en?oq=11802851

11,747,304 – IN-PROCESS QUALITY ASSESSMENT FOR ADDITIVE MANUFACTURING,
September 5, 2023
https://patents.google.com/patent/US11747304B2/en?oq=11747304

US 11,543,388 – IN-PROCESS QUALITY ASSESSMENT FOR ADDITIVE MANUFACTURING, January 3, 2023
https://patents.google.com/patent/US11543388B2/en?oq=US+11%2c543%2c388+B2+

US 11,268,931 - SEGMENTED FIELD EDDY CURRENT SENSING FOR DISPERSIVE PROPERTY MEASUREMENT AND COMPLEX STRUCTURES, March 8, 2022
https://patents.google.com/patent/US11268931B2/en?oq=US+11%2c268%2c931+

US 11,268,933 - IN-PROCESS QUALITY ASSESSMENT FOR ADDITIVE MANUFACTURING, March 8, 2022
https://patents.google.com/patent/US11268933B2/en?oq=US+11%2c268%2c933+B2+

Public Patent Applications

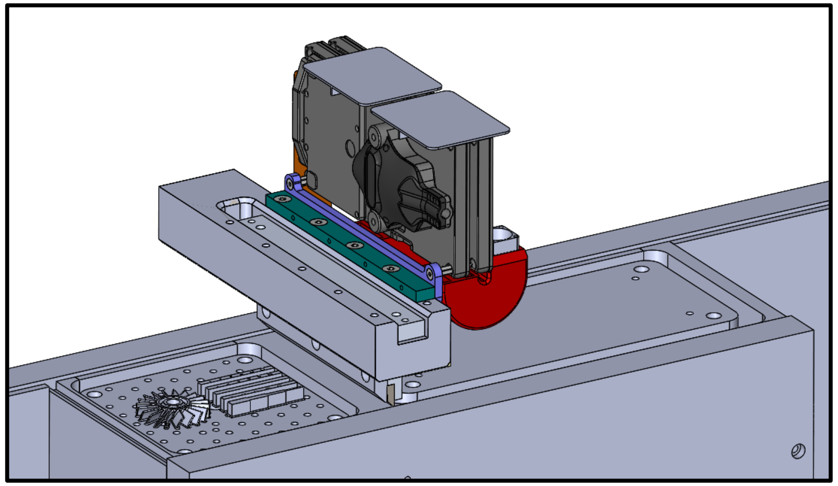
US 2023/0095662 A1 - SEGMENTED FIELD EDDY CURRENT SENSING FOR DISPERSIVE PROPERTY MEASUREMENT AND COMPLEX STRUCTURES
https://patents.google.com/patent/US20230095662A1/en?oq=US+2023%2f0095662+A1+

US 2023/0152278 A1- IN-PROCESS QUALITY ASSESSMENT FOR ADDITIVE MANUFACTURING
https://patents.google.com/patent/US20230152278A1/en?oq=US+2023%2f0152278+A1-+

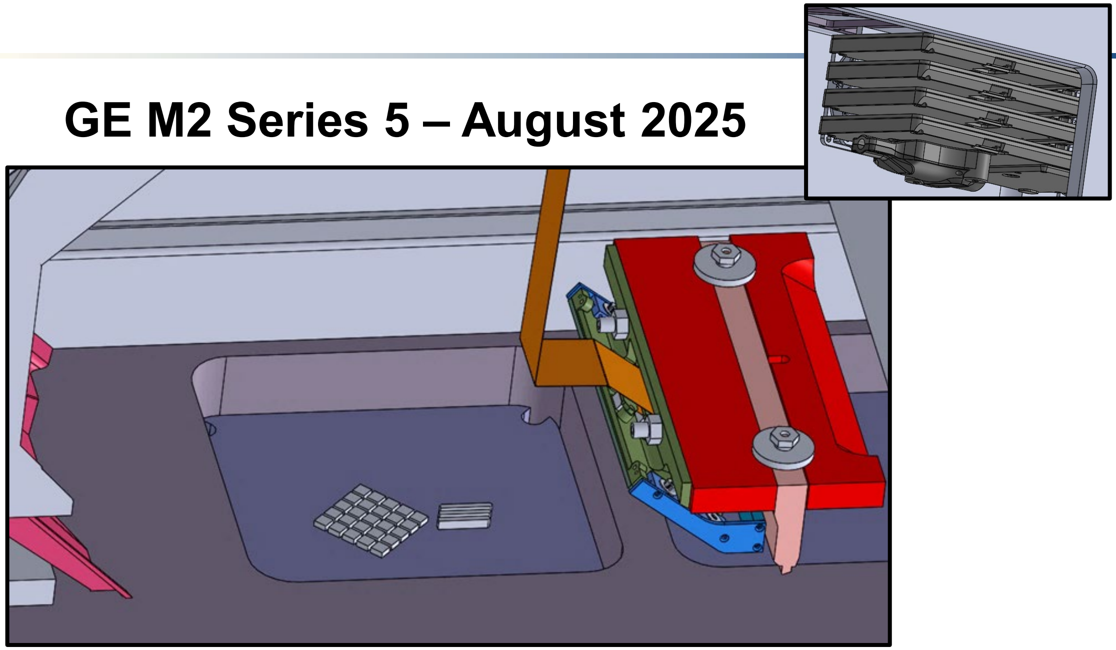
US 2018/0264590 A1 - IN SITU ADDITIVE MANUFACTURING PROCESS SENSING AND CONTROL INCLUDING POST PROCESS NDT
https://patents.google.com/patent/US20180264590A1/en?oq=US20180264590A1

Example LPBF Installations

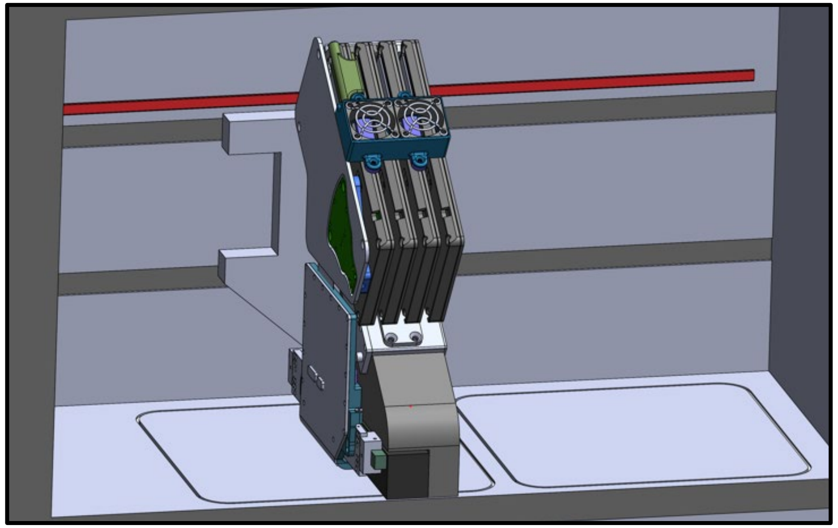
UDRI DART 2 – February 2025



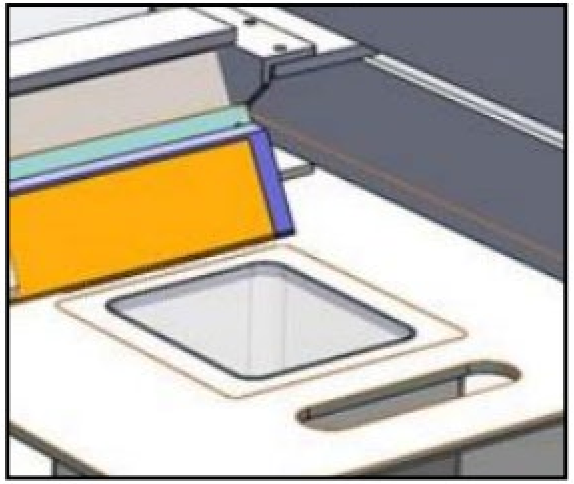
GE M2 Series 5 – August 2025



EOS M 290 – November 2025

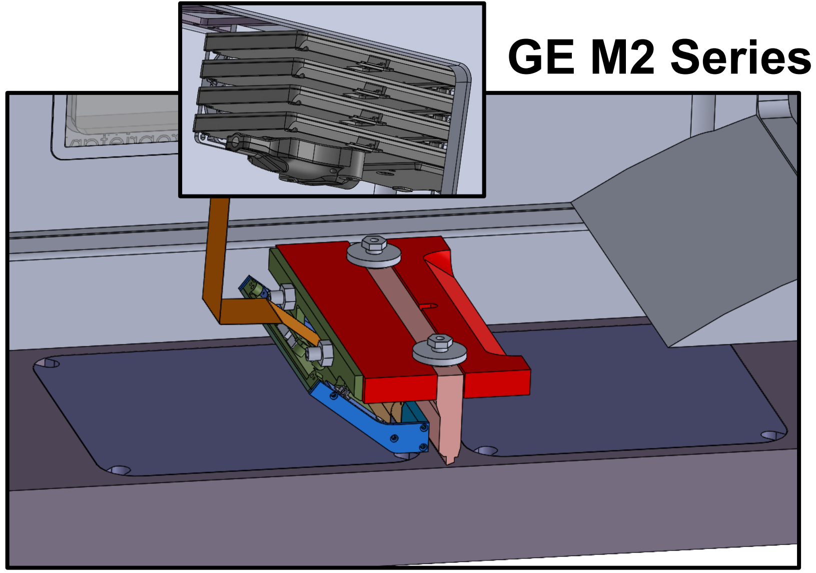


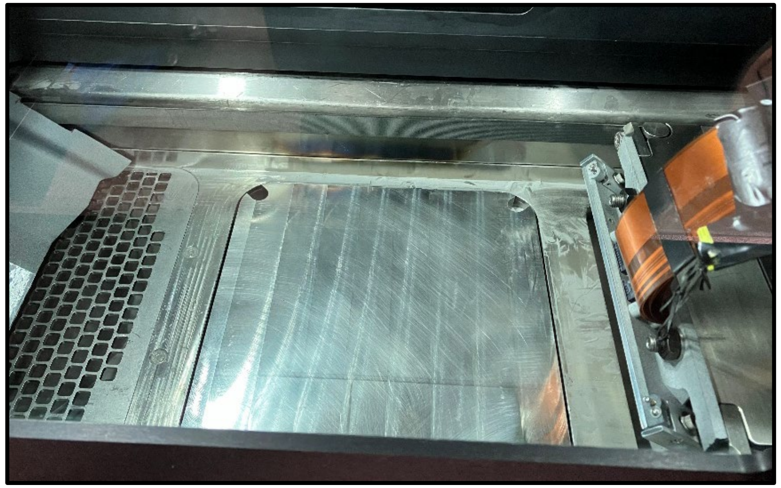
SLM 125 – 2022 - 2023



Completed 2025 GS9000 LPBF Installations / Demonstrations

GE M2 Series 5 – August 2025





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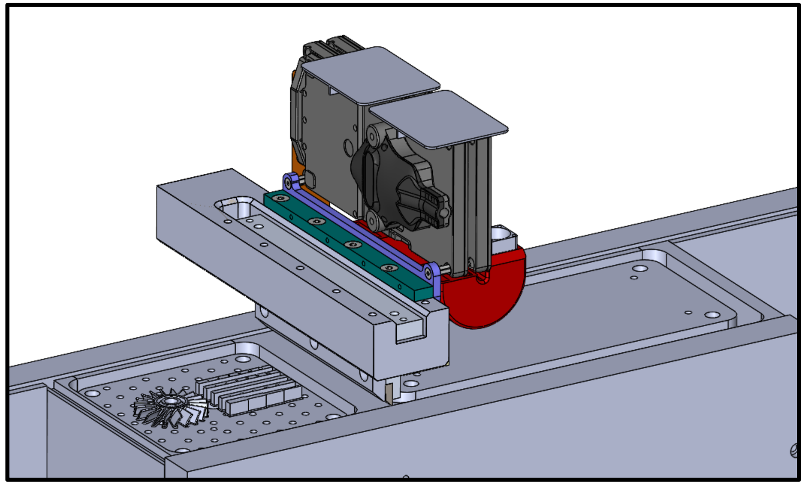

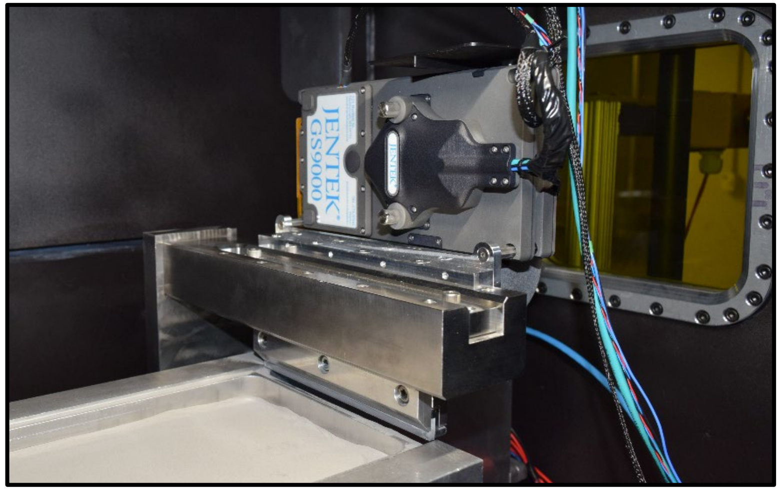

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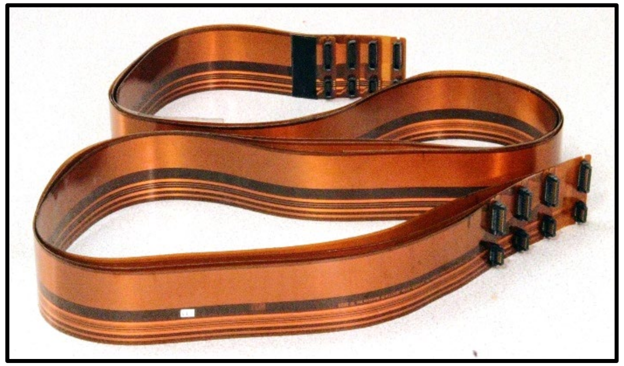
GE M2 Series 5 Installation Components

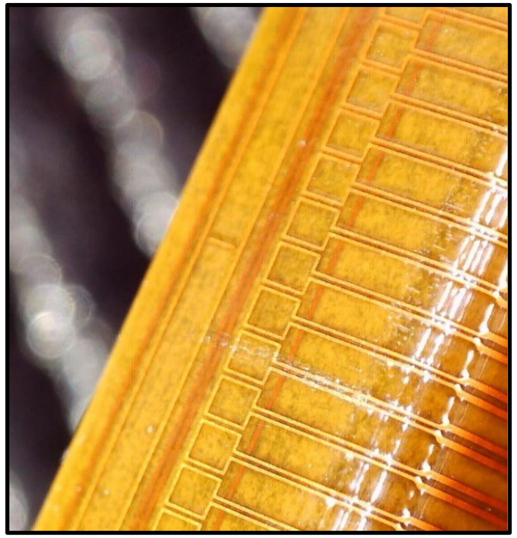
GS9000 Board Stack

Sensor Mount Kit

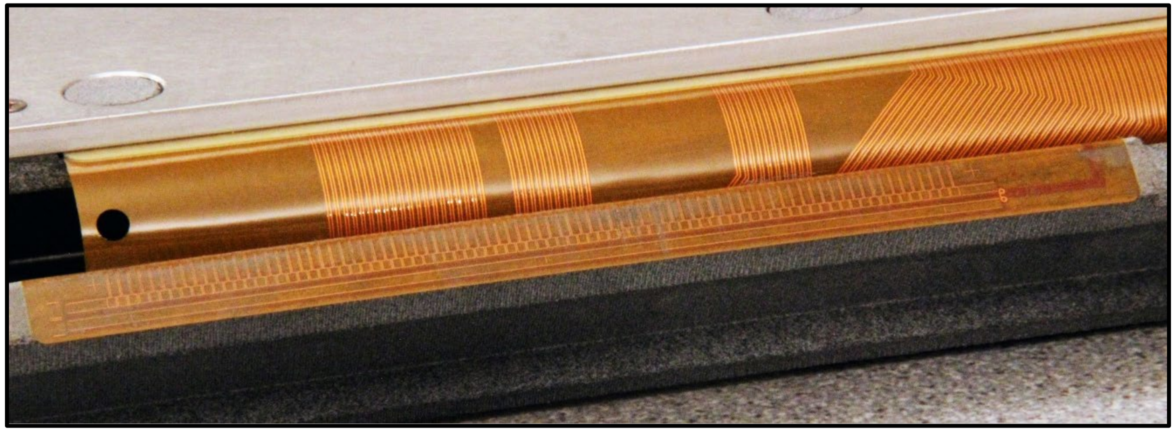
Flex Cables (optional)



79-Channel Sensor Array



79-Channel Sensor Array



MWM-Array Technology Advantages

- **Conductivity Correlation with properties**

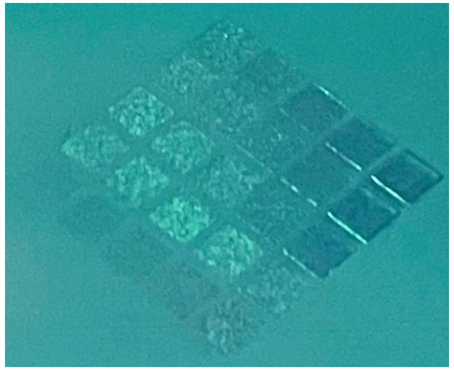
- **Local defect detection using z-directed (preferred direction) filtering, prep for ML / AI**

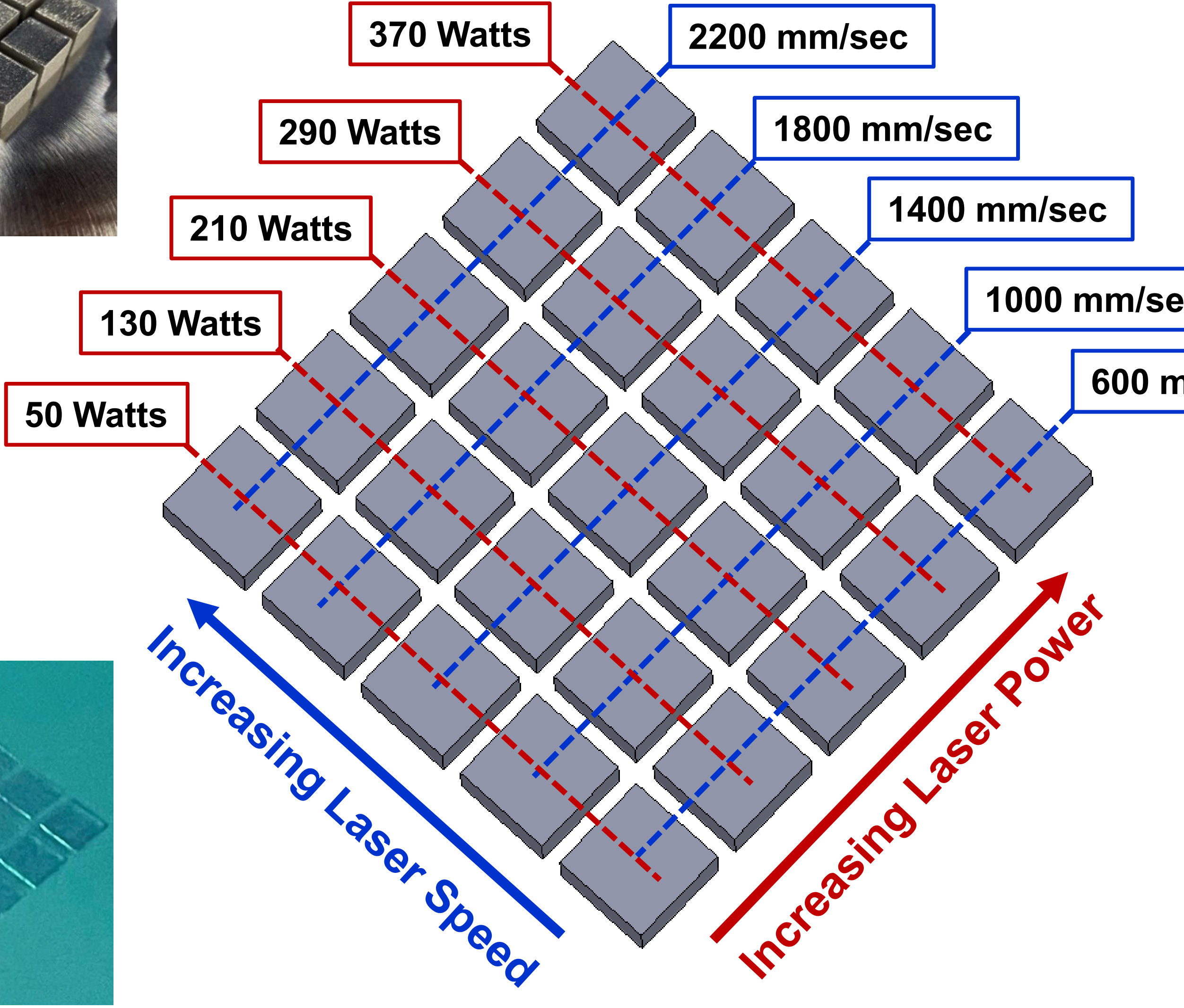
- Sub-pixel geometric imaging for edges
  and small features *(longer term development;*
  likely requires fusion with optical or IR imaging)

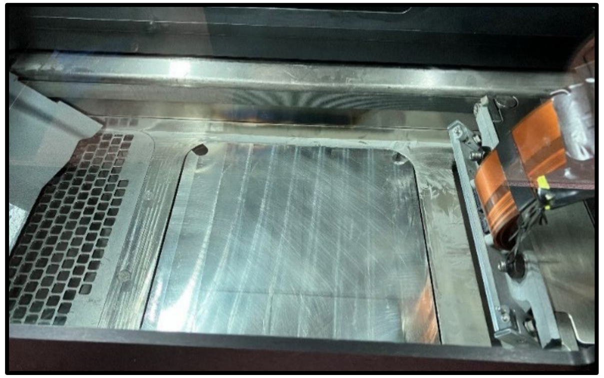
Conductivity Mapping (Varied Laser Power and Speed)

Photo

Photo

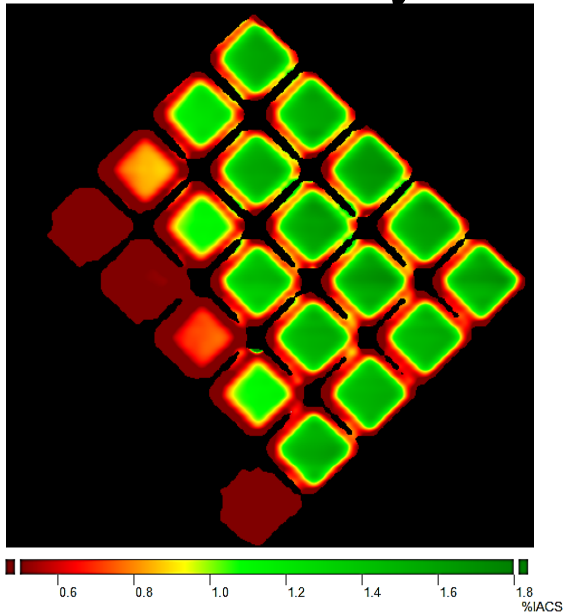






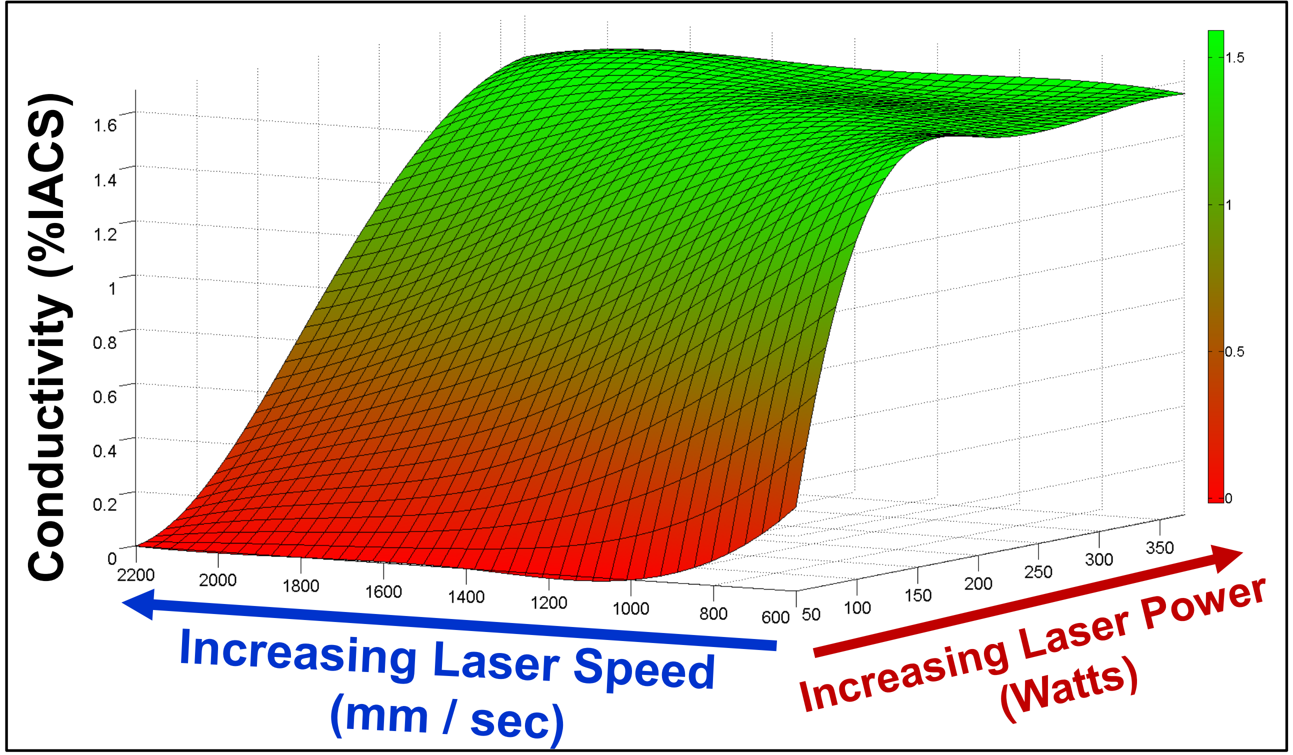
GE M2 Installation

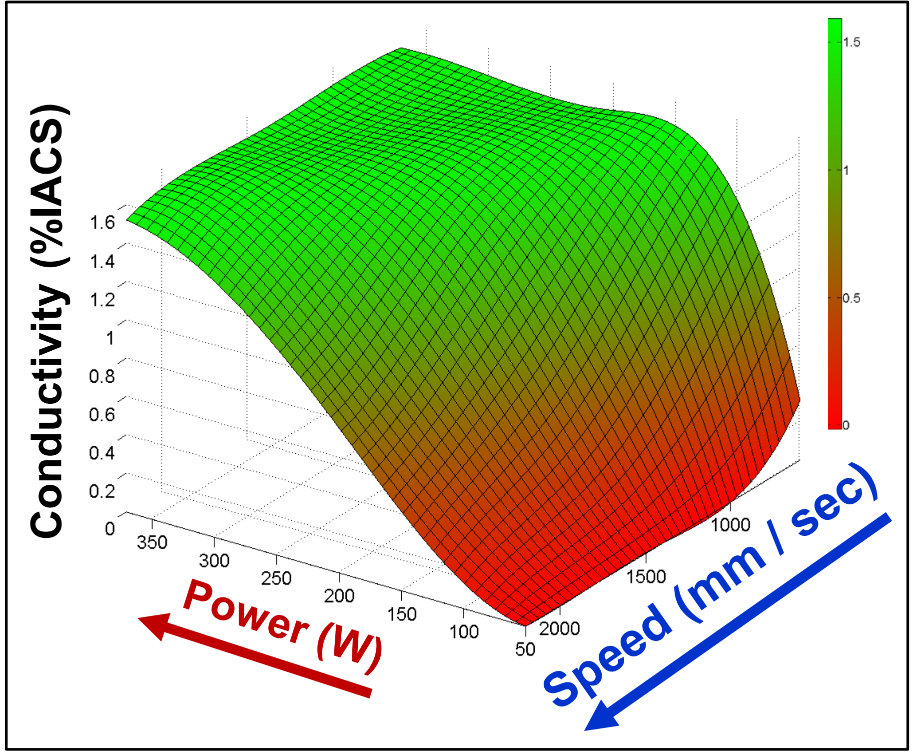
Conductivity

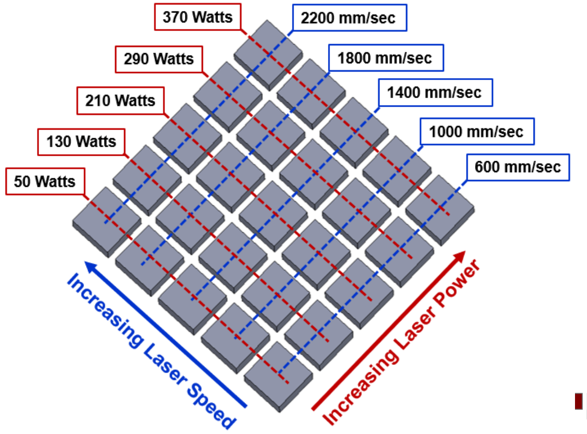


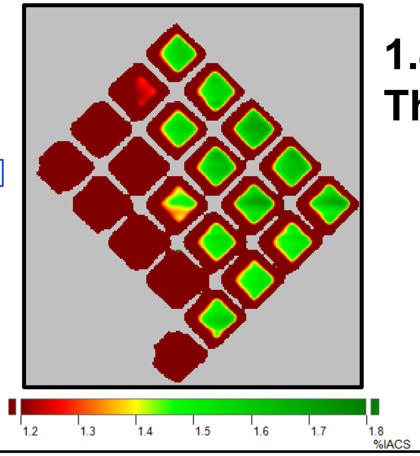
MWM-Array

Conductivity Surface by Laser Parameters

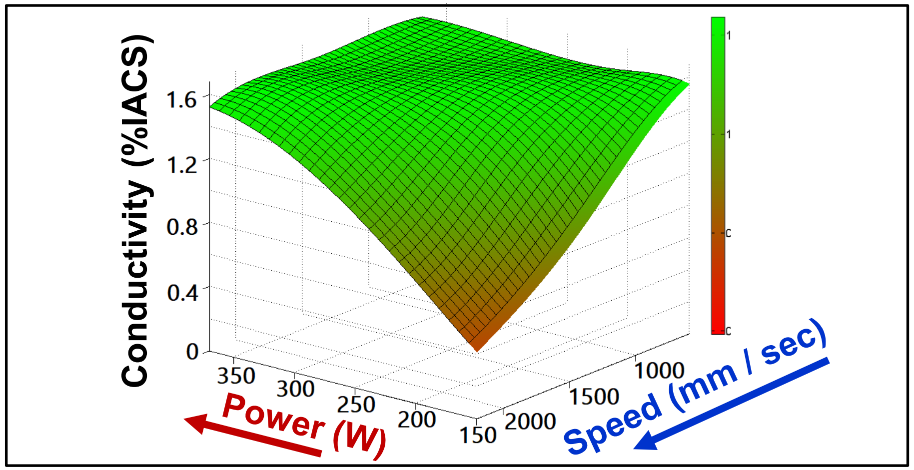








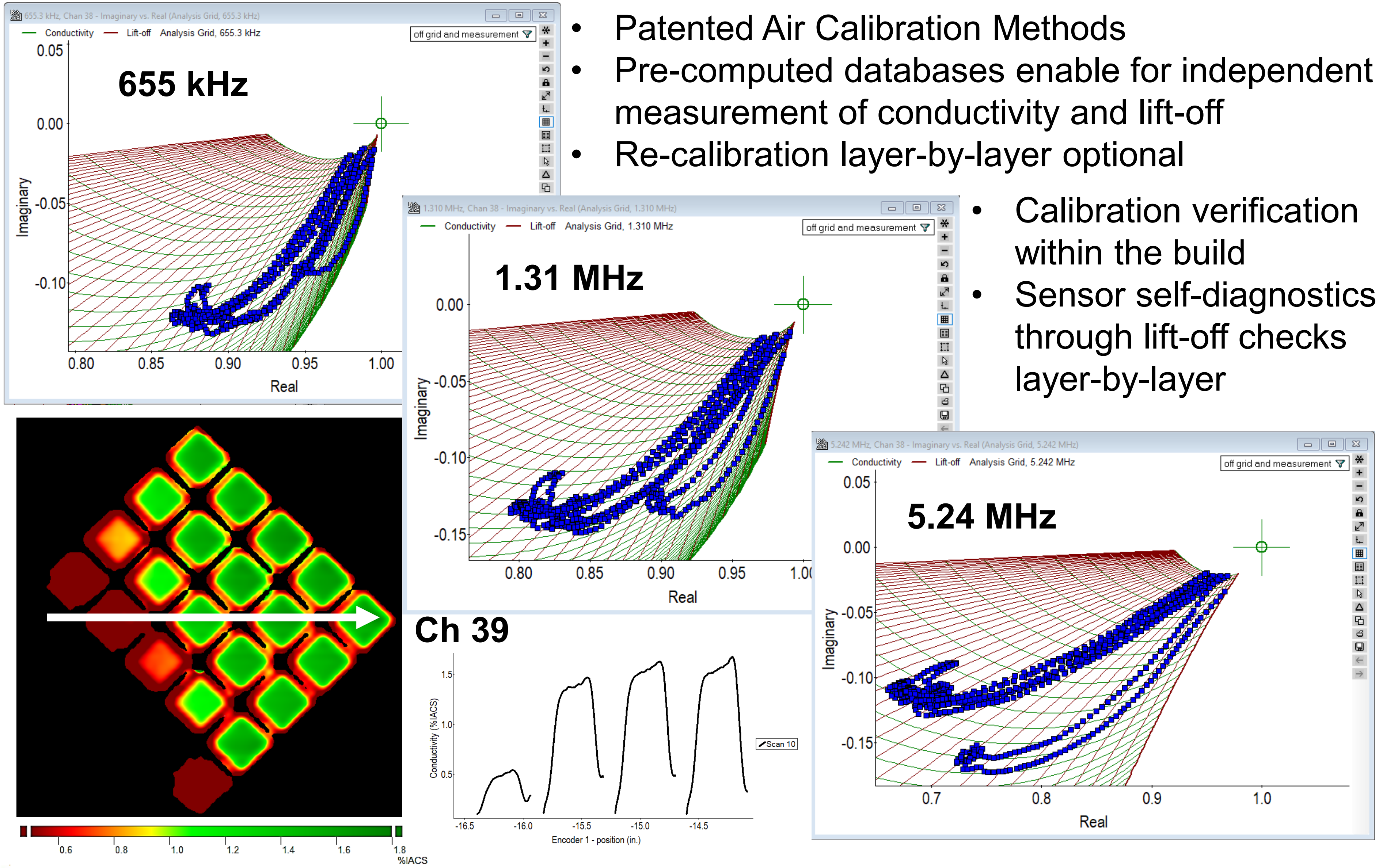
1.41 %IACS Threshold



Air Calibration per ASTM E2338

- Patented Air Calibration Methods
- Pre-computed databases enable for 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



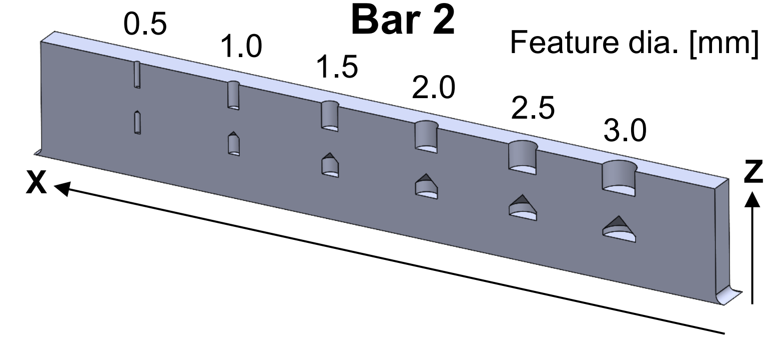
UDRI DART 2 Void Detection/Imaging Example

- Example Vertical Slices (x-z plane)

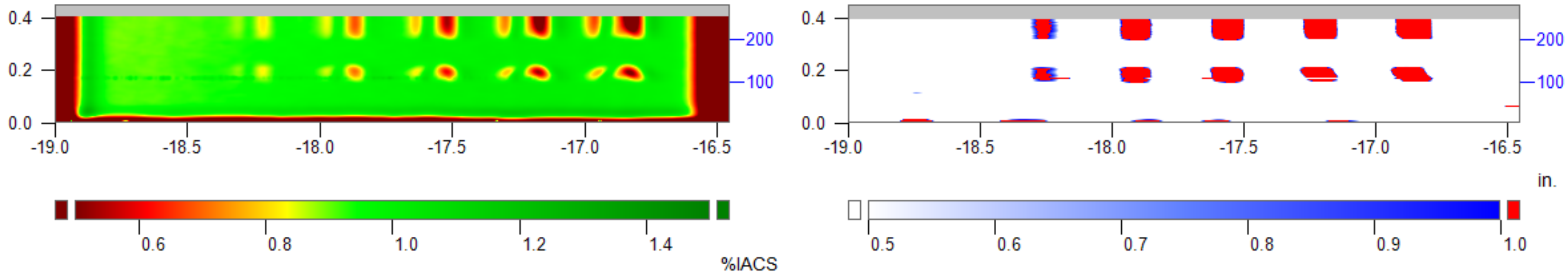
Effective Conductivity

Machine Learning Using Simple Shape Filter (5 MHz only)

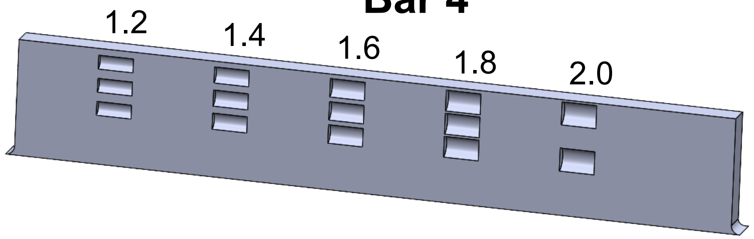
Bar 2



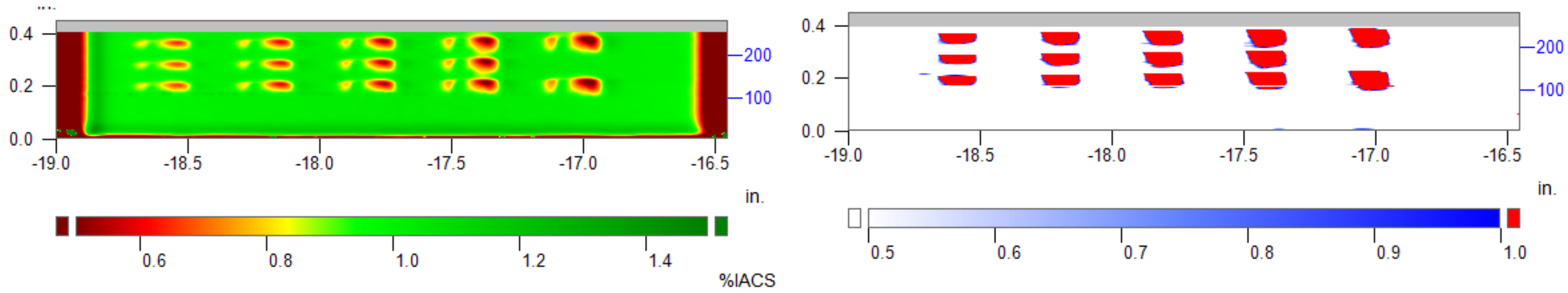
Bar 2 (Chan 29)



Bar 4

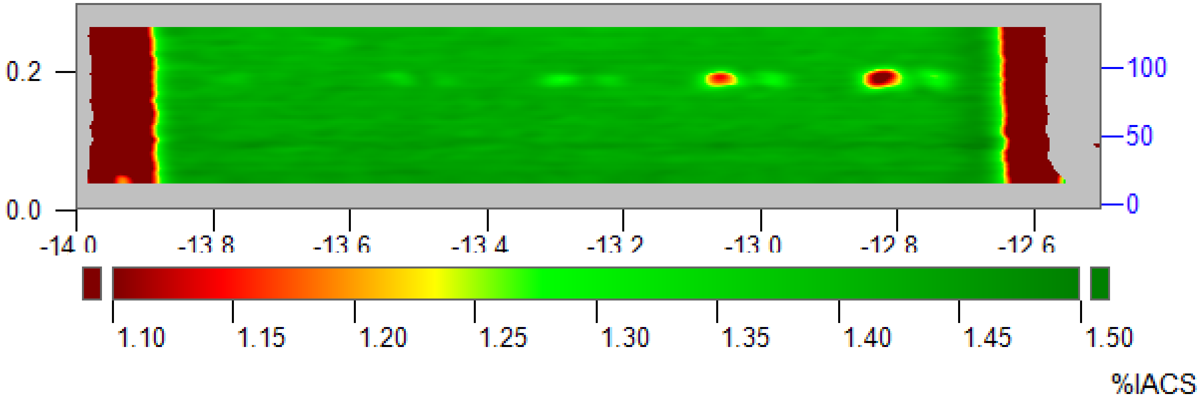


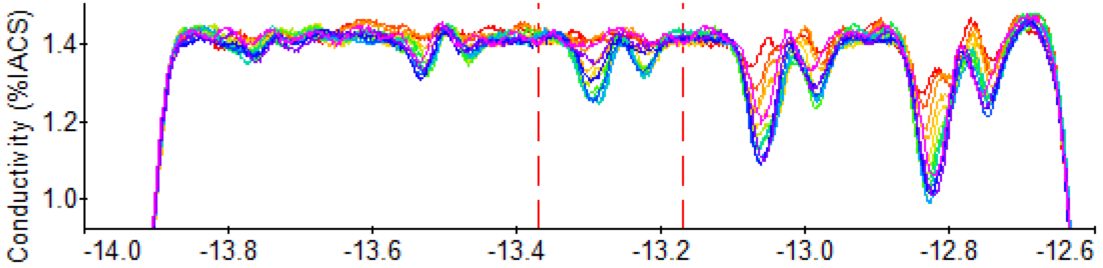
Bar 4 (Chan 15)



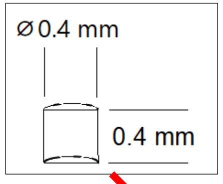
Astro Build 3 Void Detection/Imaging Example

Effective Conductivity

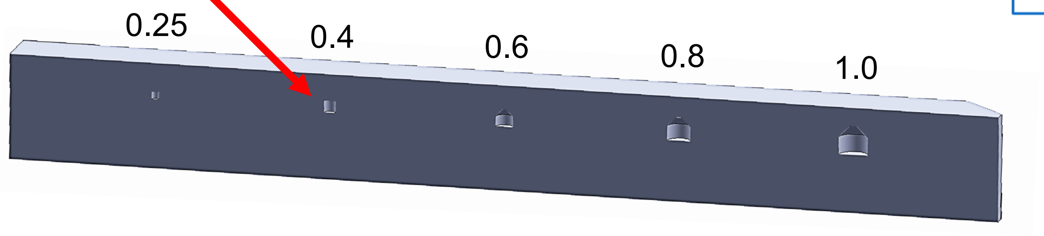




Position (in.)

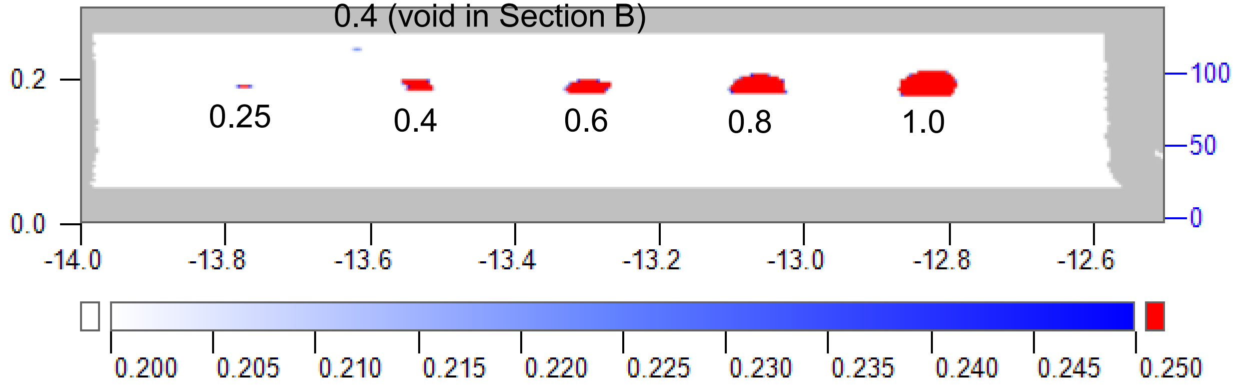


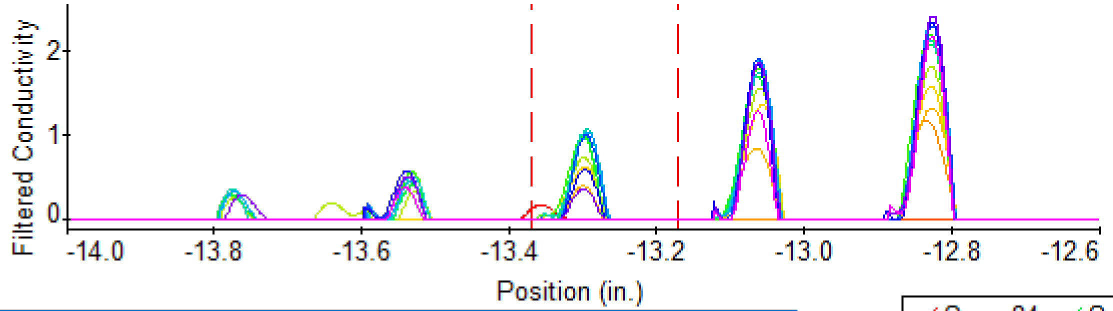
Bar 2: larger voids have chamfered tops
Void dia. and total height. [mm]

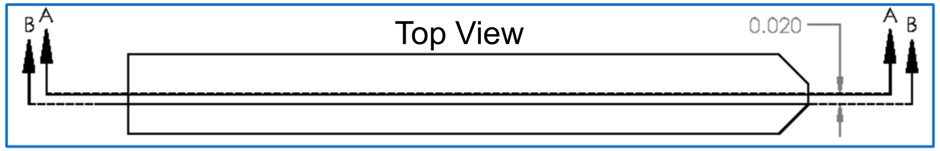


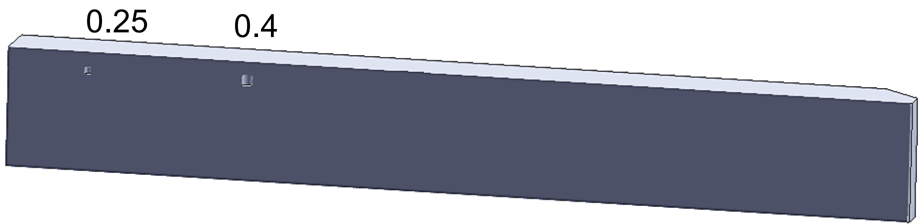
Section A

Simple Shape Filter (5 MHz only)





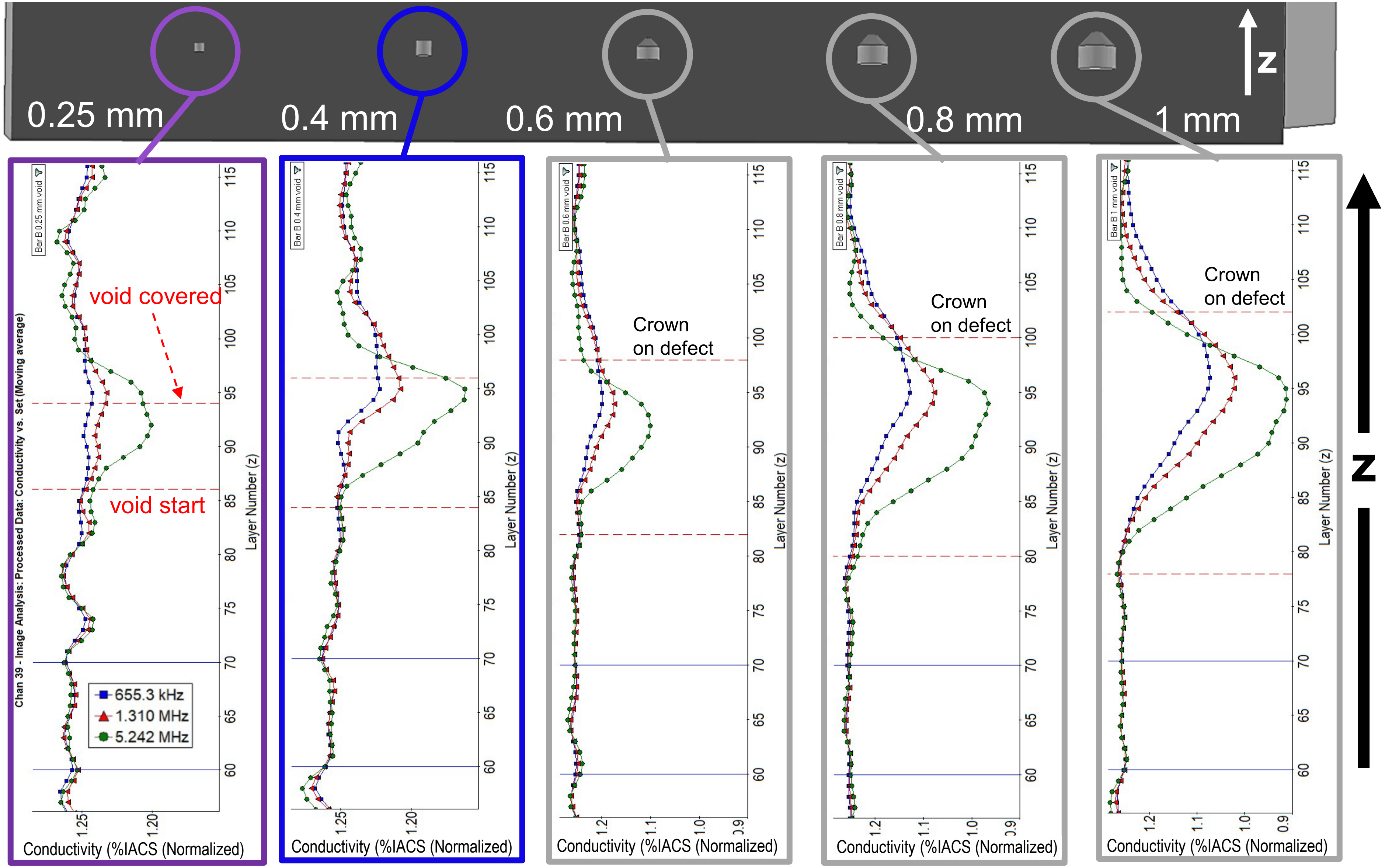




Section B

CT Replacement - Local Defect Detection

(including covered defect detection, using JENTEK z-directed visualization)



2pt z-direction moving average applied to this data

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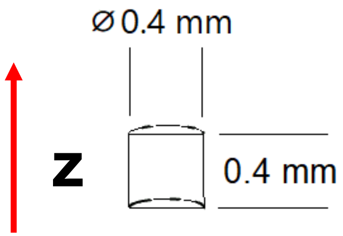
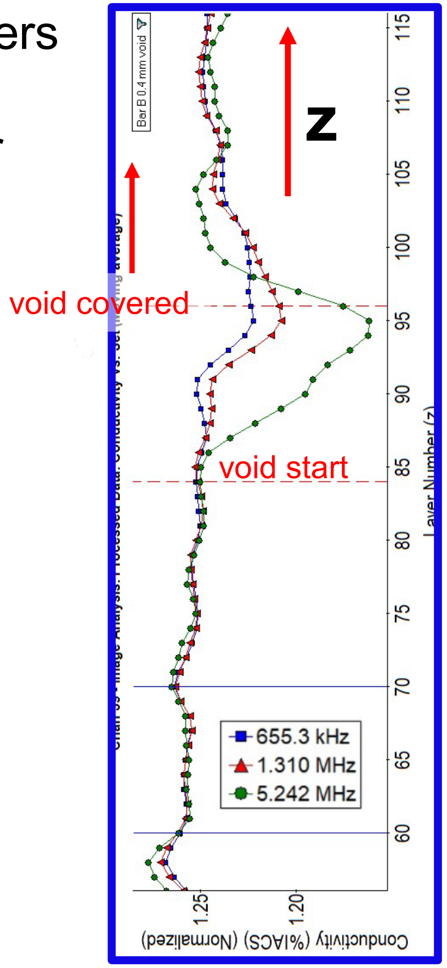
Covered Void Detection / z-Directed Visualization

Unique capability to detect covered defects 4-10 layers below current processing layer

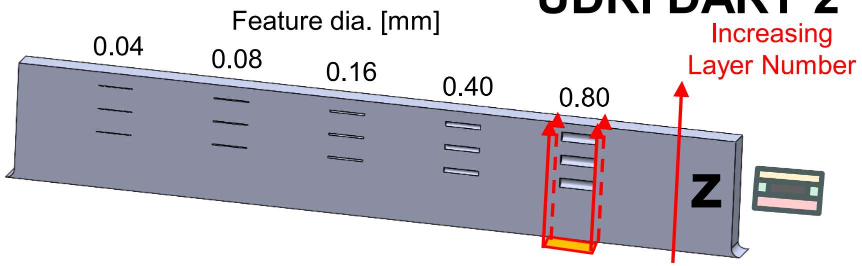


GE M2 Series 5

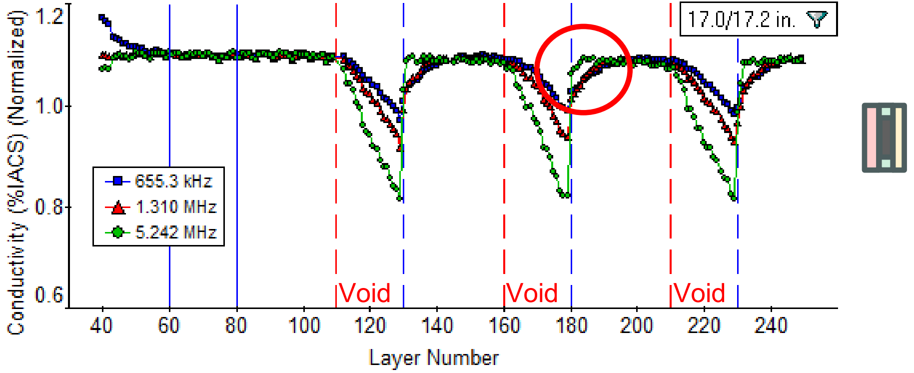
0.4 mm dia. void

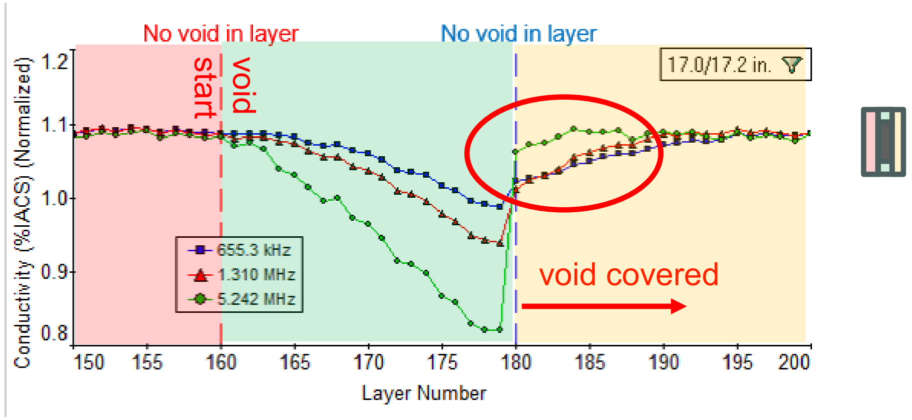


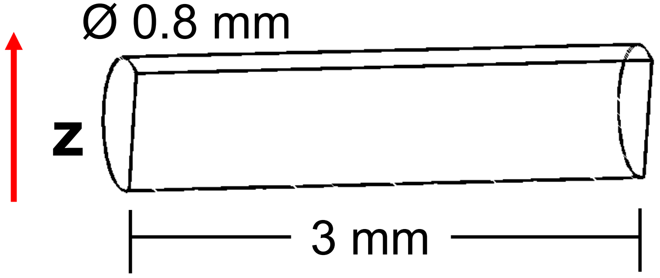
UDRI DART 2



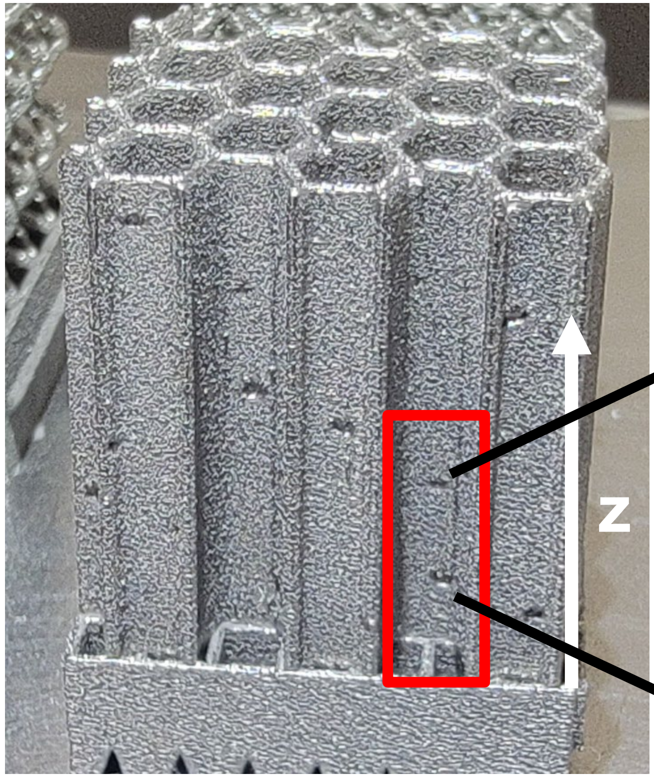
Bar 3: Channel 22, 0.8 mm dia. voids



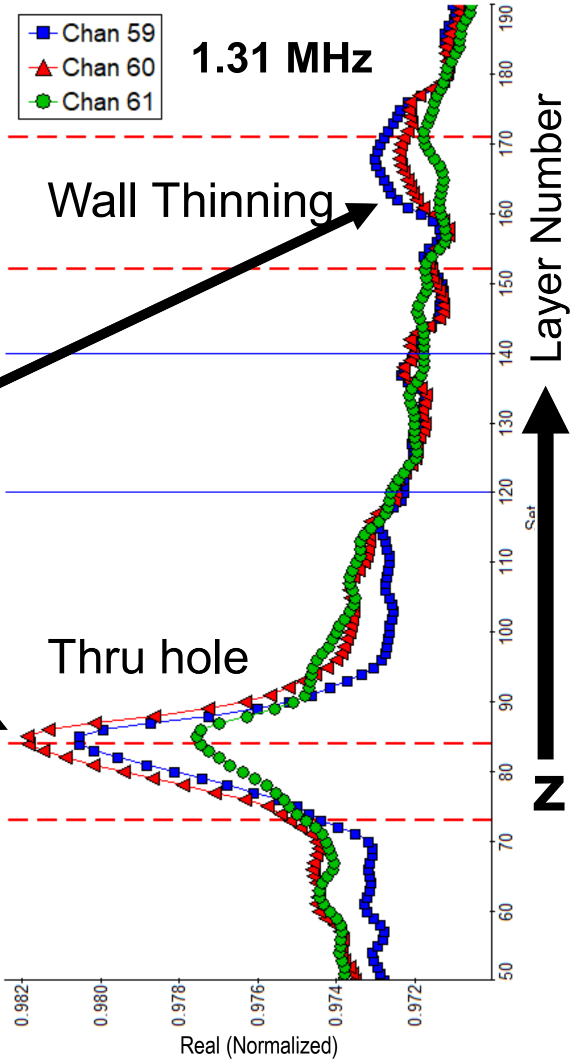




z-Directed Data Interpretation

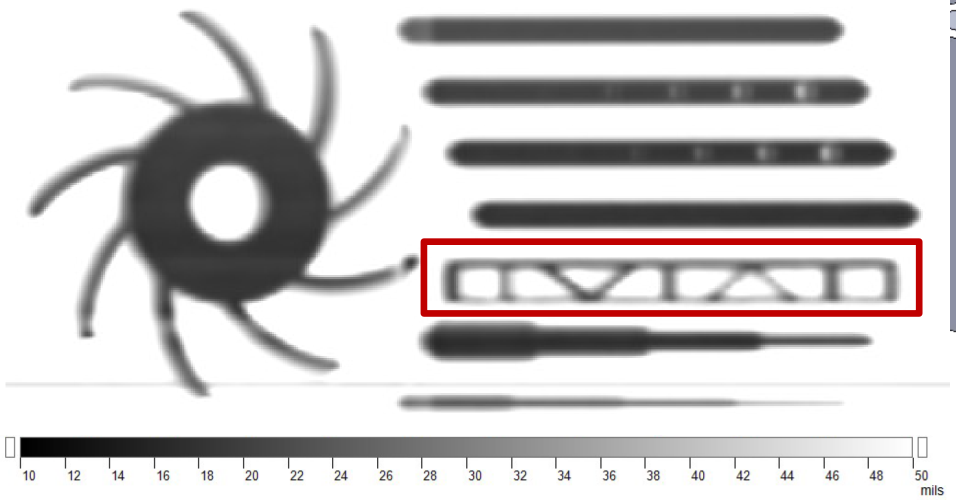


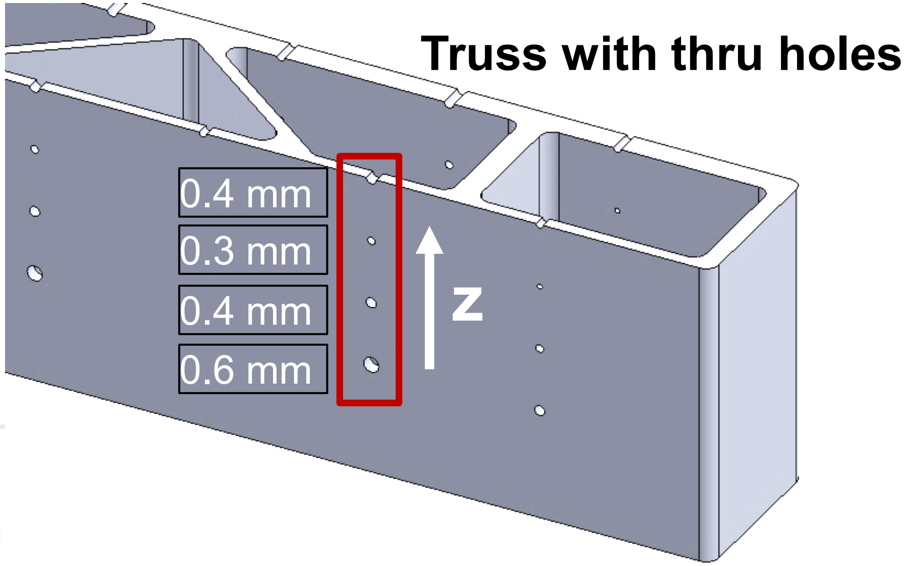
Upper wall thinning
Lower thru hole
approx. 0.5 mm diameter



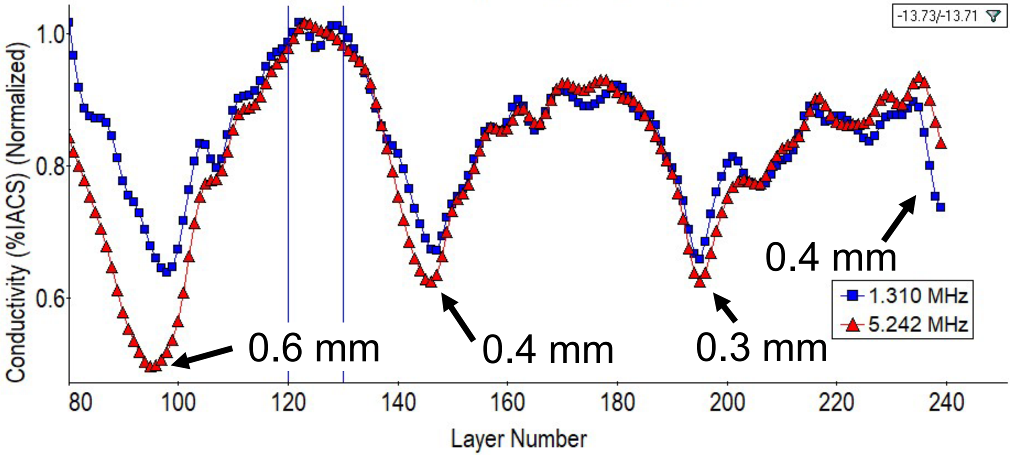
- z-Directed data generated by averaging in the xy-plane
- z-Directed filtering not yet applied – requires training on representative defects
- JENTEK Preferred direction filtering follows geometrically consistent features to prepare data for ML / AI training

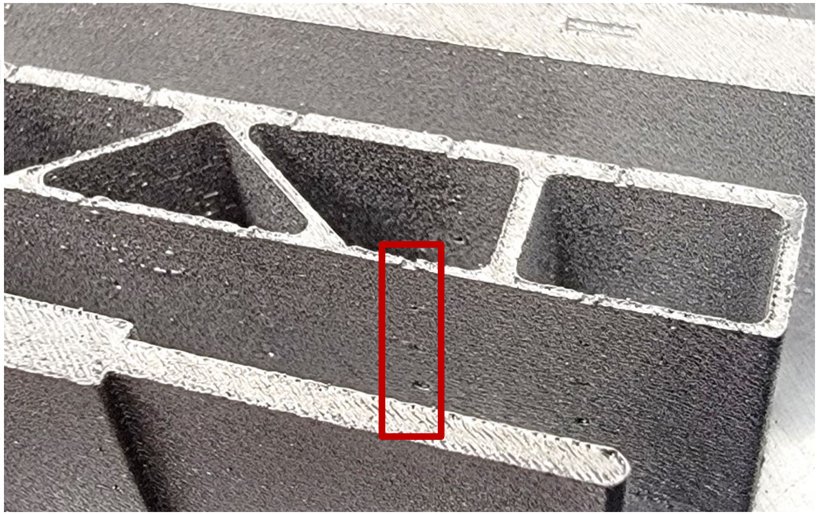
Example z-Directed Local Defect Visualization




Truss with thru holes

Conductivity vs. Layer # (z)

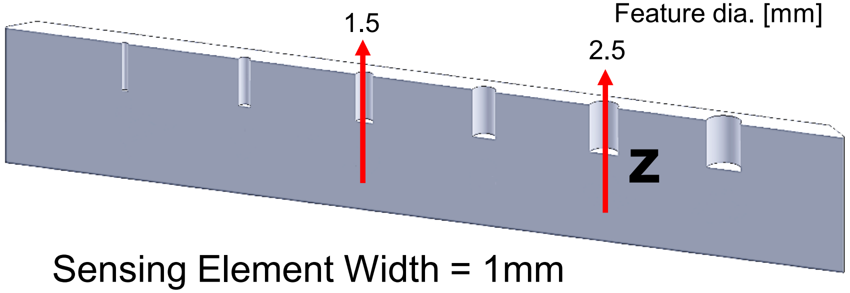




- Z-Directed Filtering not yet implemented. Requires training / machine learning

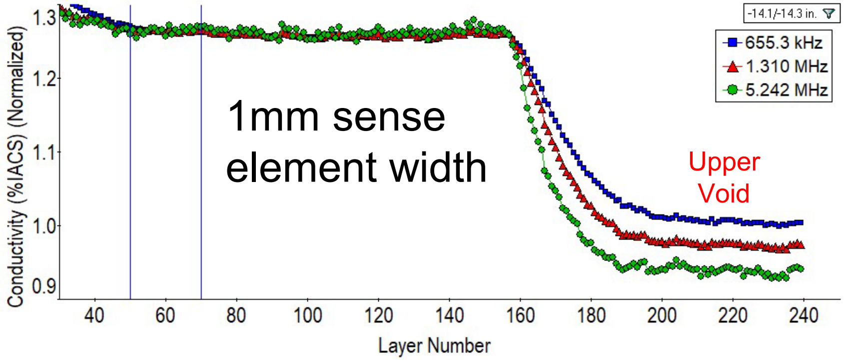
Comparison – GE M2 Series 5 vs. UDRI DART 2 Data

Build 1: GE M2 Series 5

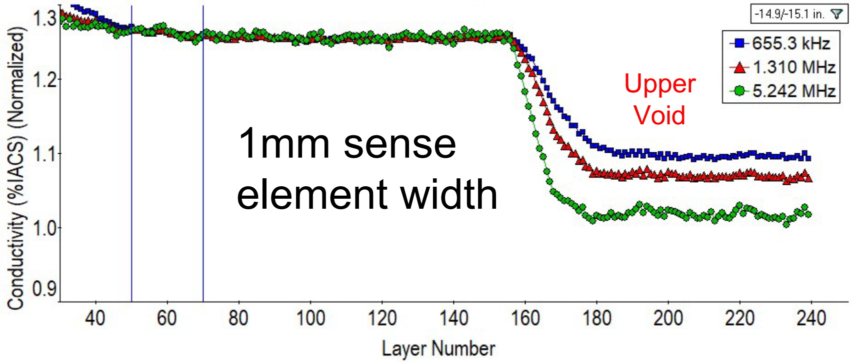


Sensing Element Width = 1mm

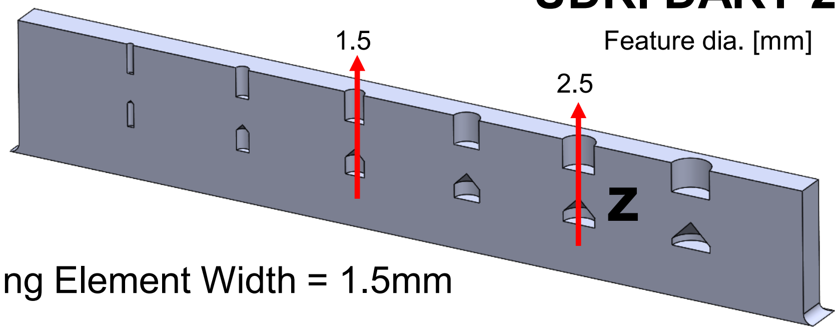
Channel 57, 2.5 mm dia. void



Channel 57, 1.5 mm dia. void

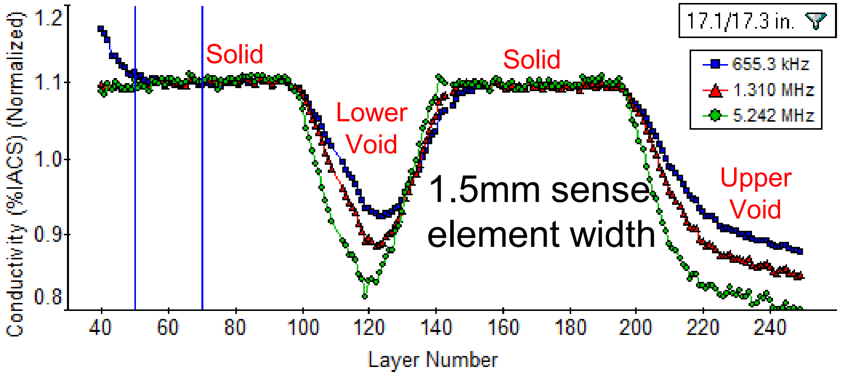


UDRI DART 2

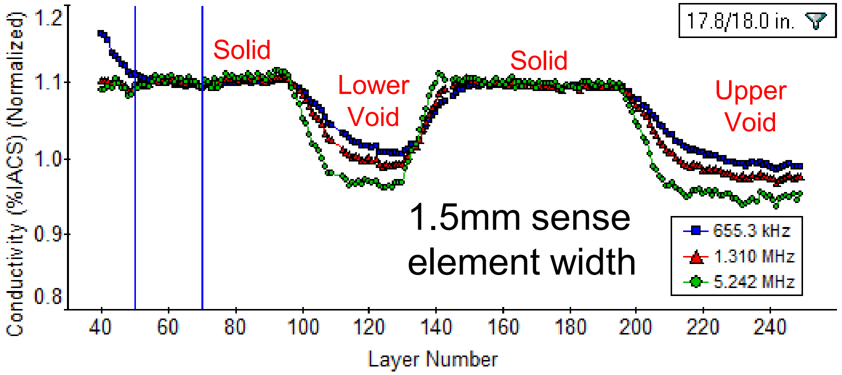


Sensing Element Width = 1.5mm

Channel 36, 2.5 mm dia. voids



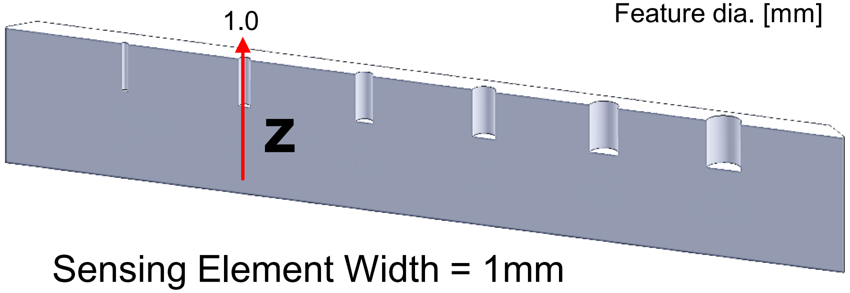
Channel 36, 1.5 mm dia. voids



JENTEK® Sensors, Inc.

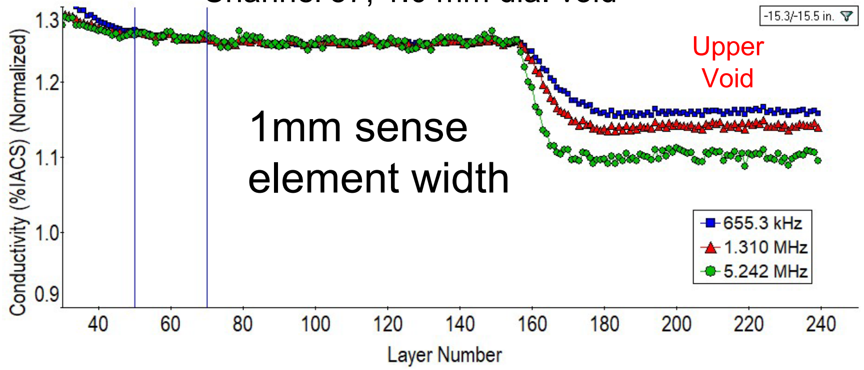
Comparison – GE M2 Series 5 vs. UDRI DART 2 Data

Build 1: GE M2 Series 5

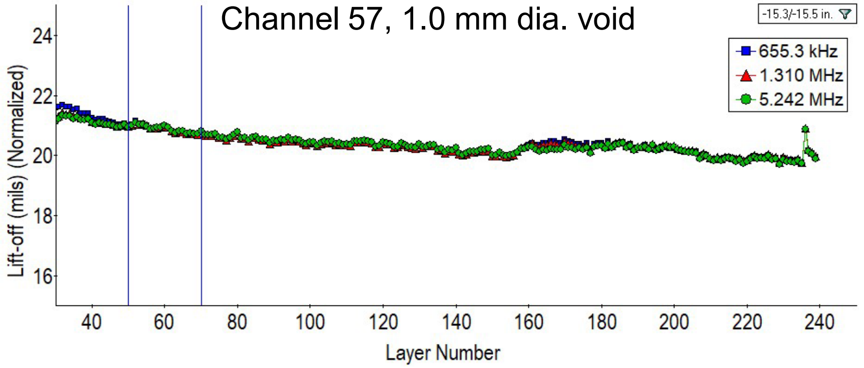


Sensing Element Width = 1mm

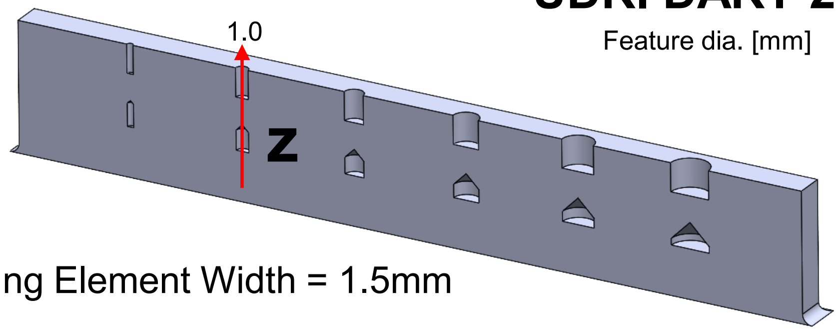
Channel 57, 1.0 mm dia. void



Channel 57, 1.0 mm dia. void

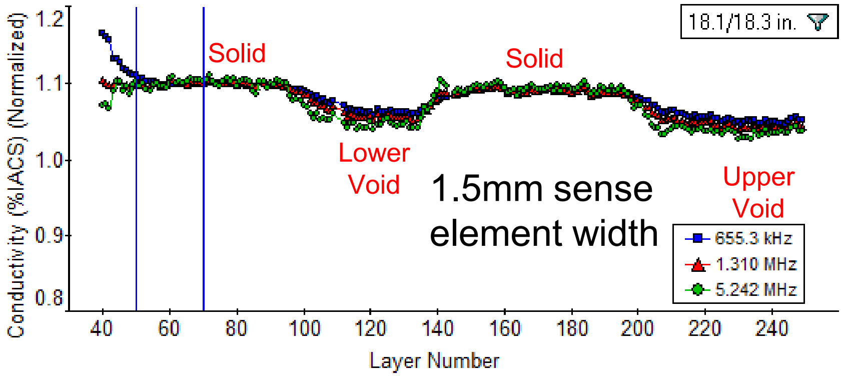


UDRI DART 2

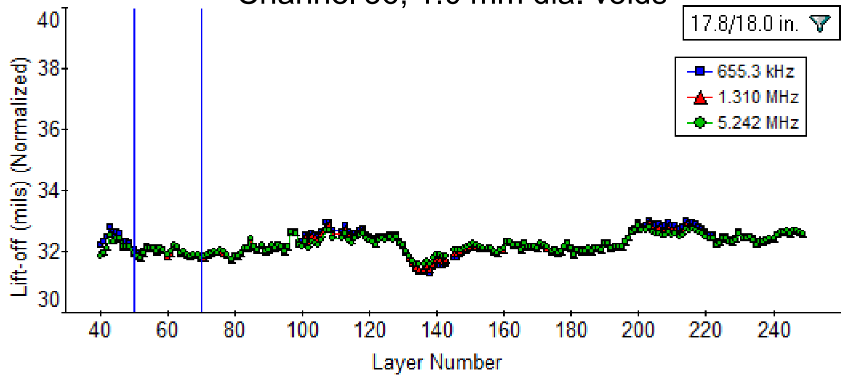


Sensing Element Width = 1.5mm

Channel 36, 1.0 mm dia. void

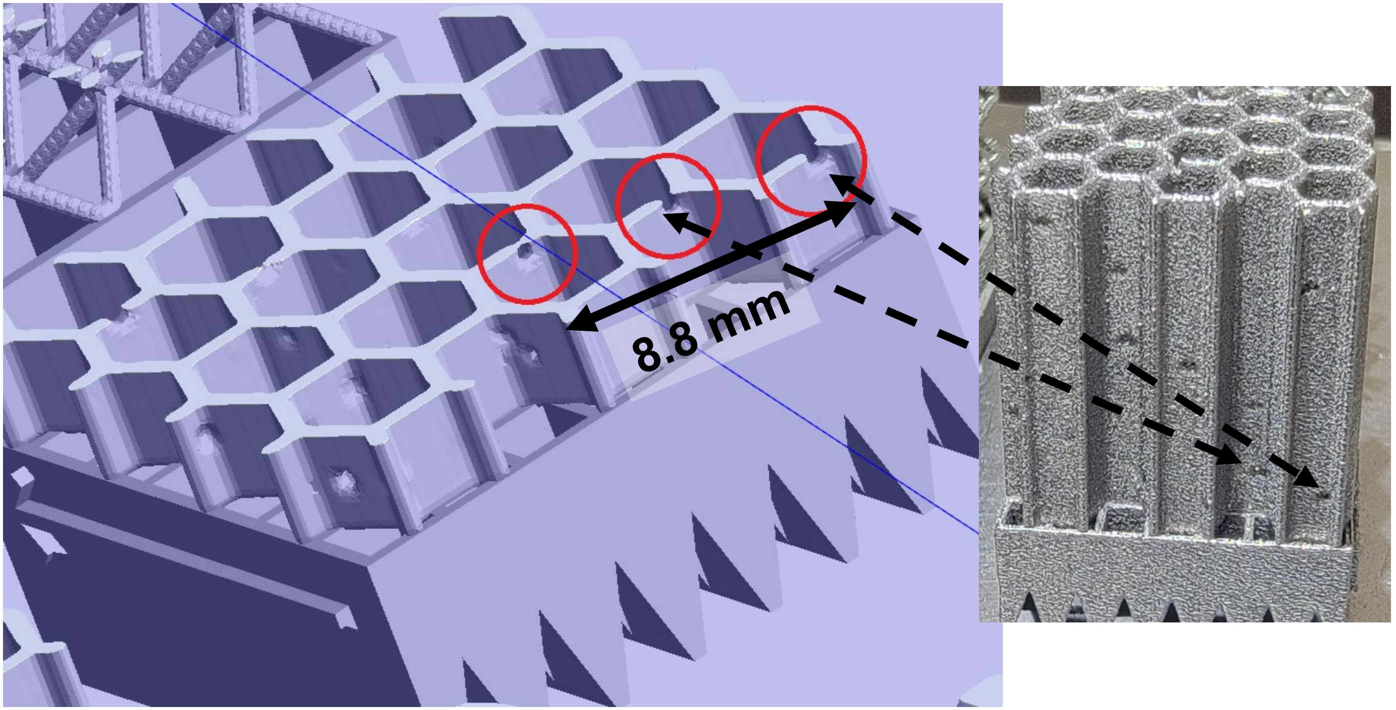


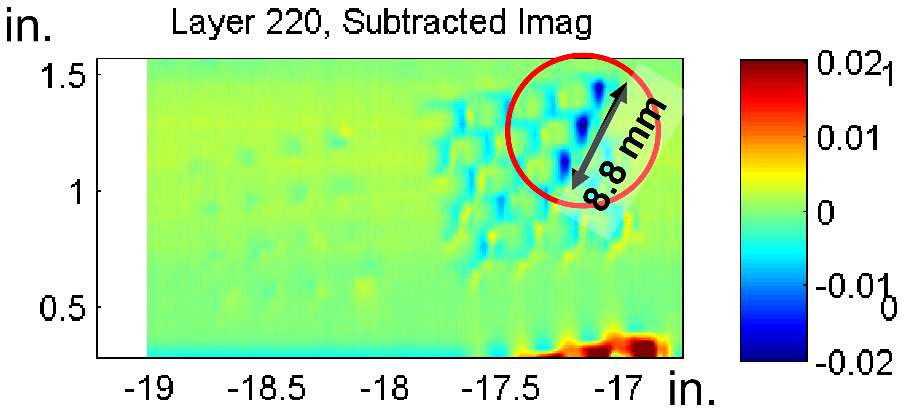
Channel 36, 1.0 mm dia. voids

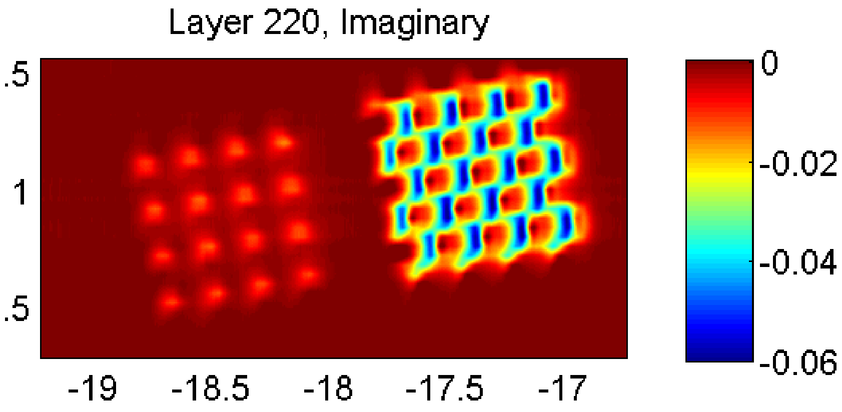


Astro Demo Hex Data Interpretation

- Wall thickness: ~0.6mm
- Defects: 0.35mm, 0.5mm, 0.55mm thru wall
- 1.3 MHz Image Subtraction
- Preferred Direction Filtering not applied, requires training



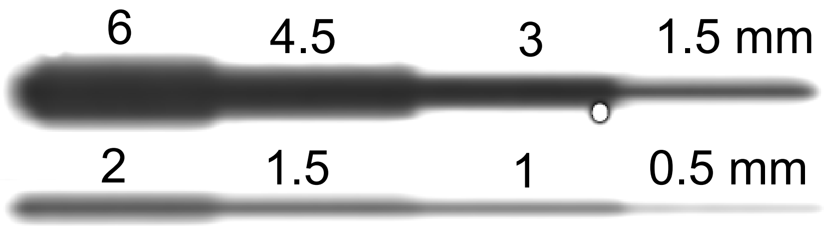


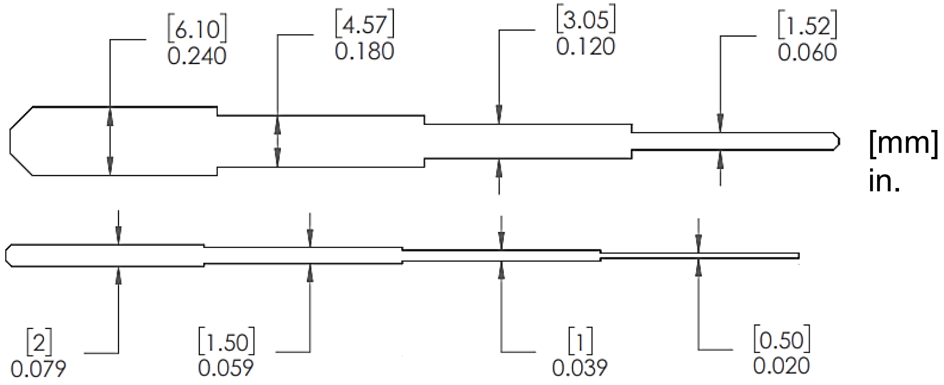


Sub-Pixel Geometric Imaging

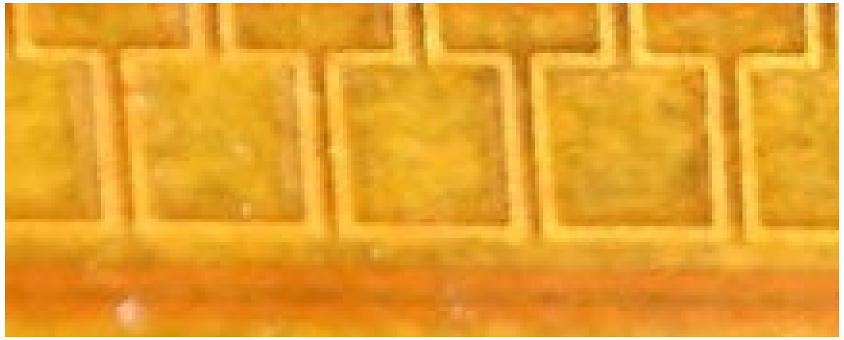
(likely requires fusion with optical or IR imaging)

Wall Thickness Step Wedges

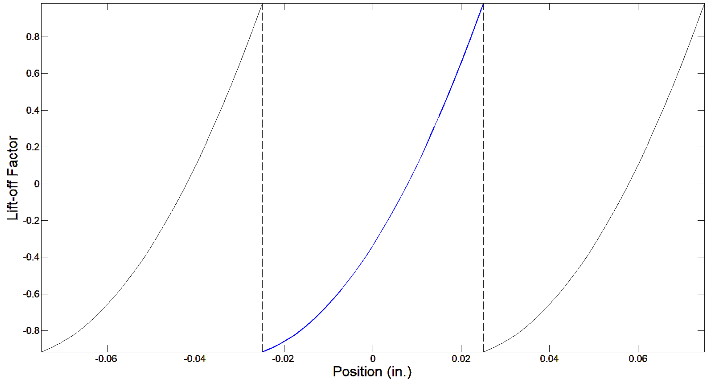




No Image Sharpening Applied



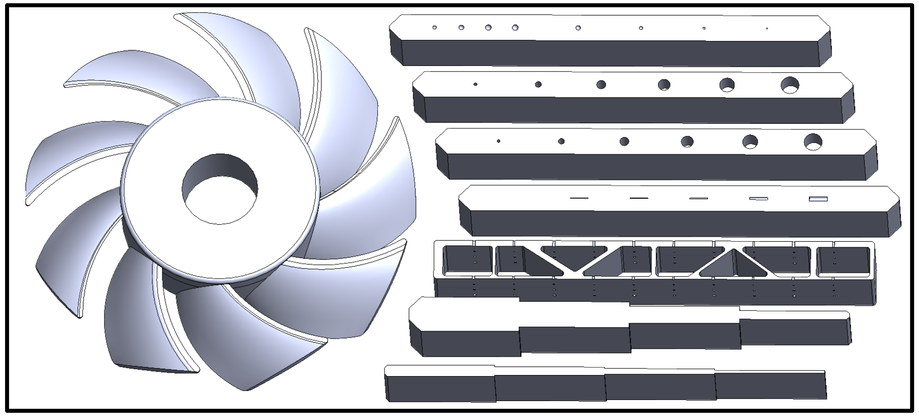
- Continuous variation of the effective lift-off response within the sensing element footprint to edges or sub-pixel features enables image sharpening
- Example MWM-Array sensing element response for edges
- The zero of the position corresponds to the sensing element being centered on the edge



Analog Sub-Pixel Response Enables Sharpening

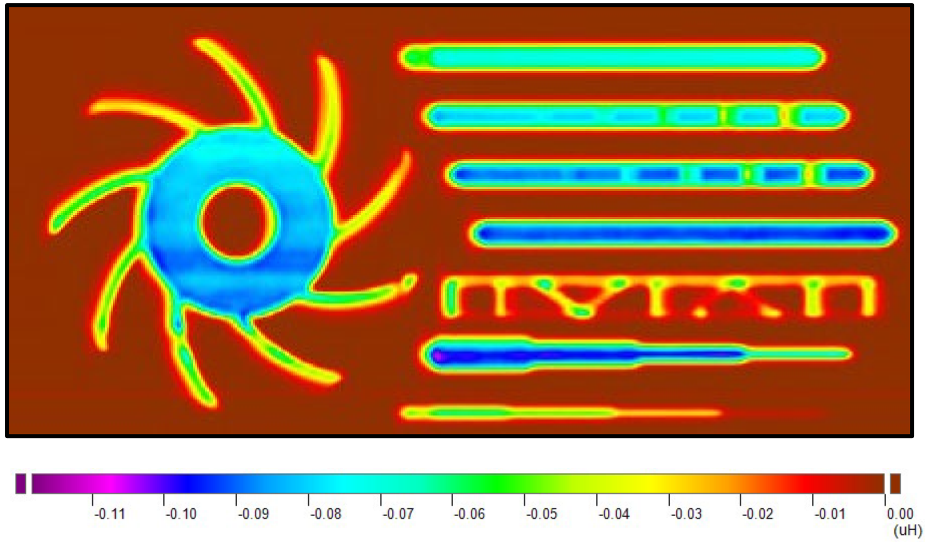
Real-time Data Viewing

Model

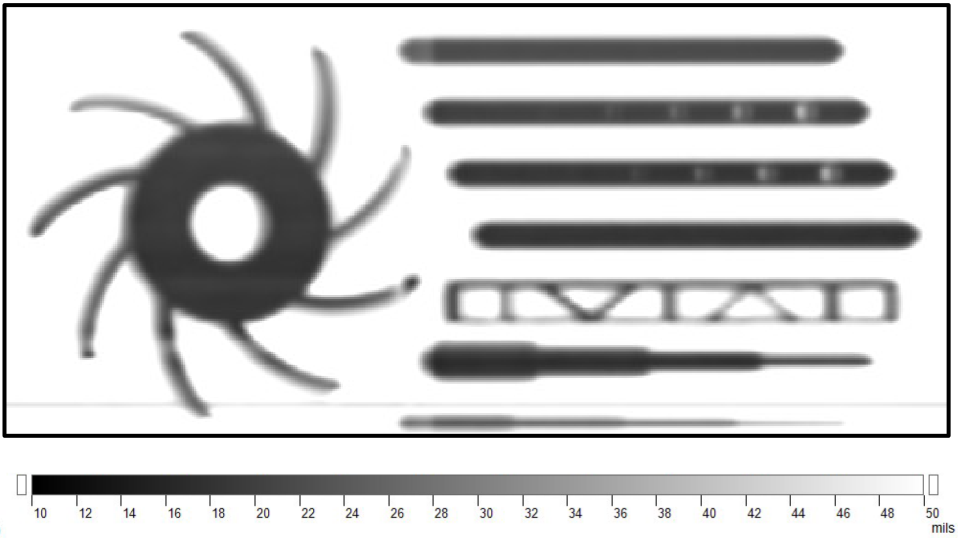


Photo

Real-Time Raw Data Layer 190 (Imag)

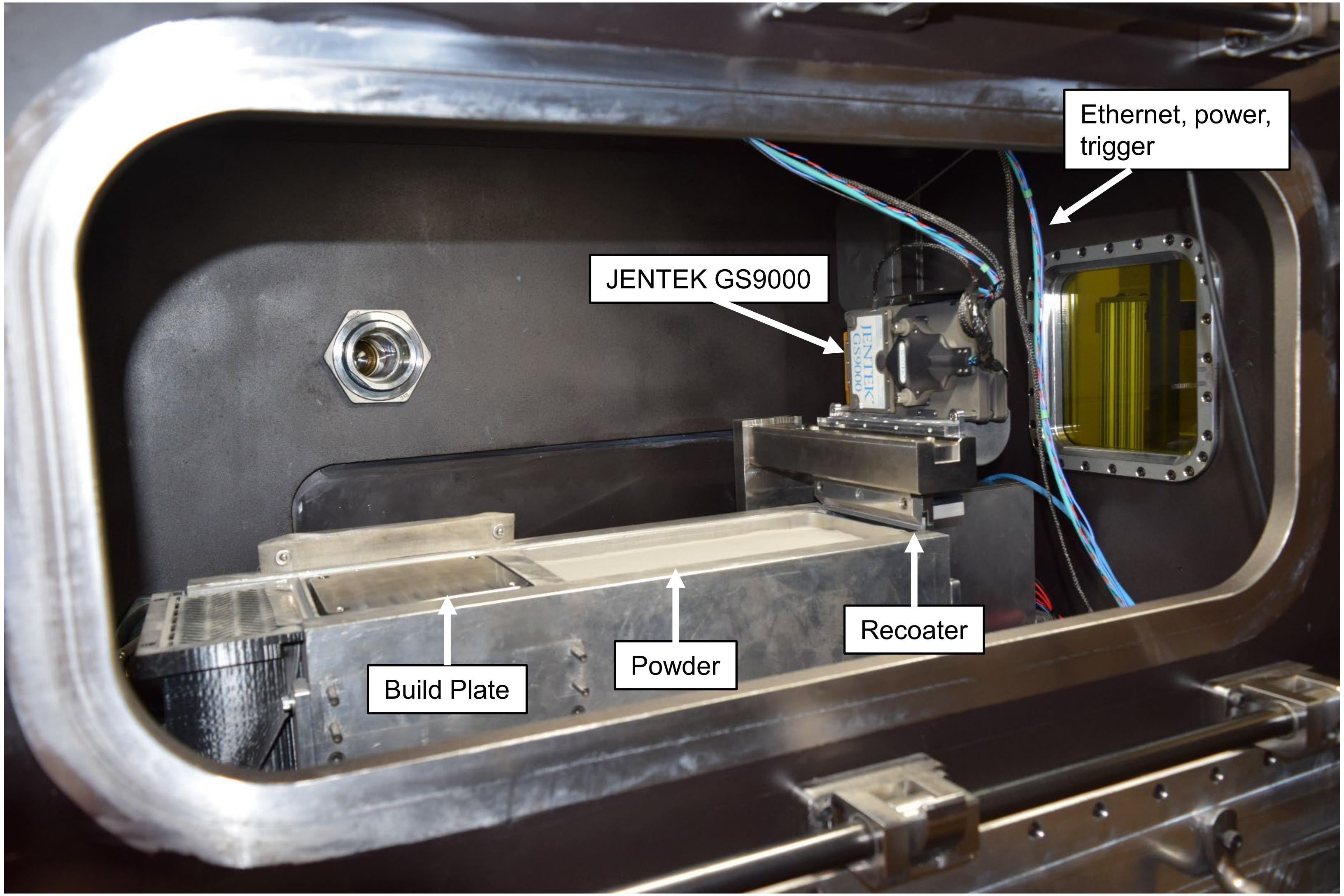


Processed Data Layer 190 (Lift-off)



MWM-Array Images without Sub-pixel sharpening

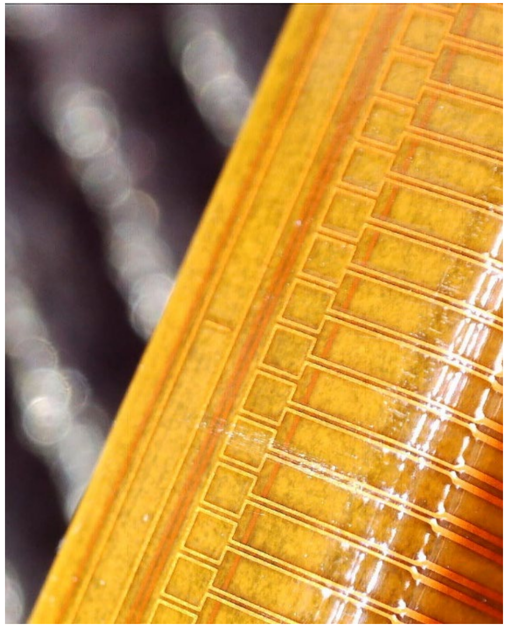
Previous GS9000 Installation on DART 2 at UDRI

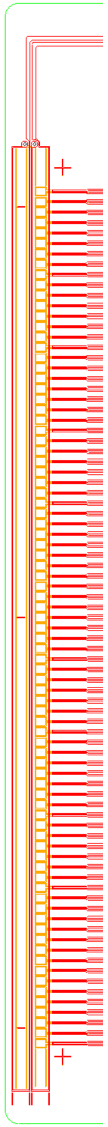


Astro Demo: M2 Series 5 Build Configurations

- Inspection Details
  - Scan speed: 55 mm / sec [1.9 in/sec] (did NOT alter standard motion rate for recoater)
  - Data Rate: ~0.043mm [0.0017 in.] increments in scan direction (1,280 meas / sec.)
  - Frequencies: 655 kHz, 1.31 MHz, 5.24 MHz

- Sensor array characteristics
  - MWM-Array: FA384
  - Sense element size:
    - Recoat Direction = 1.11 mm [0.044 in.]
    - Channel Direction = 1.02 mm [0.04 in.]
  - Scan width of MWM-Array: ~80.6 mm [3.17 in.]
  - Number of channels: 79



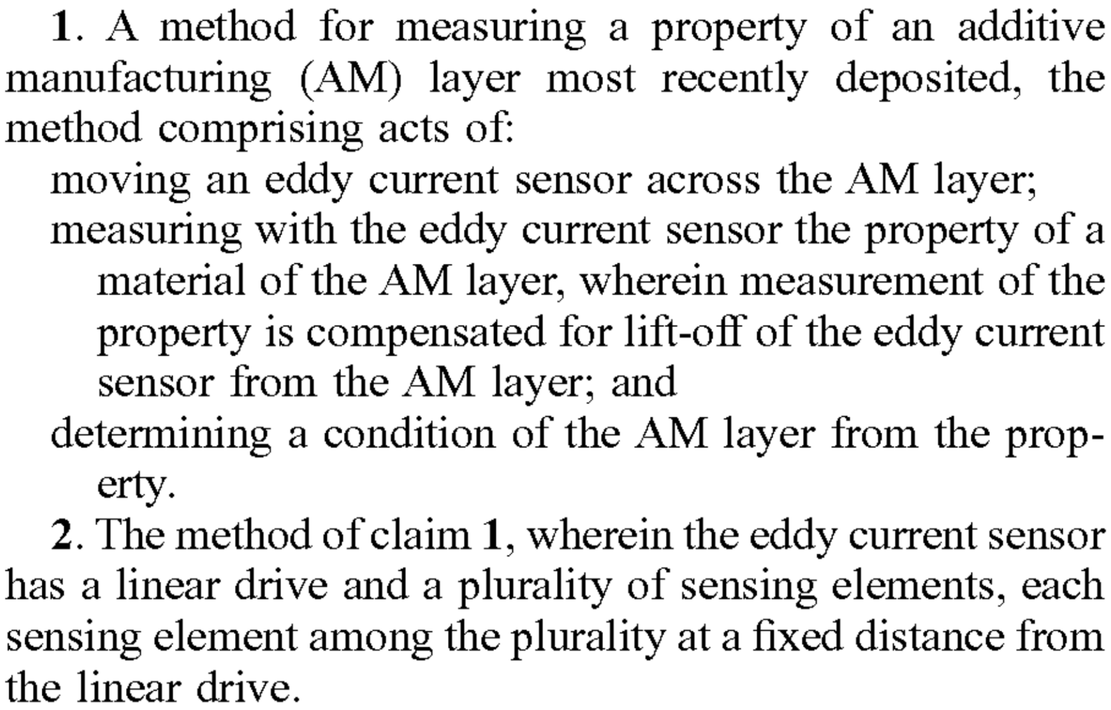


- Build details:
  - Number of Layers: 250 (Build 1), 930 (Build 2), 132 (Build 3)
  - Material: Inconel 718
  - Layer Thickness: 50 microns
  - Build plate size (for GE M2 Series 5):
    - 250 x 250 mm [9.84 x 9.84 in.]

- Other
  - Calibration
    - Air calibrations performed with sensor array in air at start of build
    - Can recalibrate for each layer/scan (not used here)
  - File size: 5 GB including basic property estimates (Build 1), 20.4 GB (Build 2), 2.23 GB (Build 3)

JENTEK Additive Manufacturing Patents

From 2016 filing
USPN 12,253,492 – *In-Process Quality Assessment for Additive Manufacturing*, Issued March 18, 2025
https://patents.google.com/patent/US12253492B2/en?oq=12253492



1. A method for measuring a property of an additive manufacturing (AM) layer most recently deposited, the method comprising acts of:

moving an eddy current sensor across the AM layer;

measuring with the eddy current sensor the property of a material of the AM layer, wherein measurement of the property is compensated for lift-off of the eddy current sensor from the AM layer; and

determining a condition of the AM layer from the property.

2. The method of claim **1**, wherein the eddy current sensor has a linear drive and a plurality of sensing elements, each sensing element among the plurality at a fixed distance from the linear drive.

Addresses all
non-contact
eddy current sensing
in LPBF

Covers
MWM-Array
specifically

Other claims include real-time control for LPBF and DED; powder analysis methods, and broad method claims for the above claims.

Thank you for your time and attention!

Non-Contact, In-Process ET-Array Methods for Industrial Processes

Presenter: Dr. Neil Goldfine, President & Chief Engineer [+]

Authors: N. Goldfine[+], A. Washabaugh[+], T. Dunford[+], T. Simon[+], S. Chaplan[+], M. Windoloski[+], H. Foelsche[+], N. Maleski[*], J. Orr[*], S. Mirmasoudi[*]

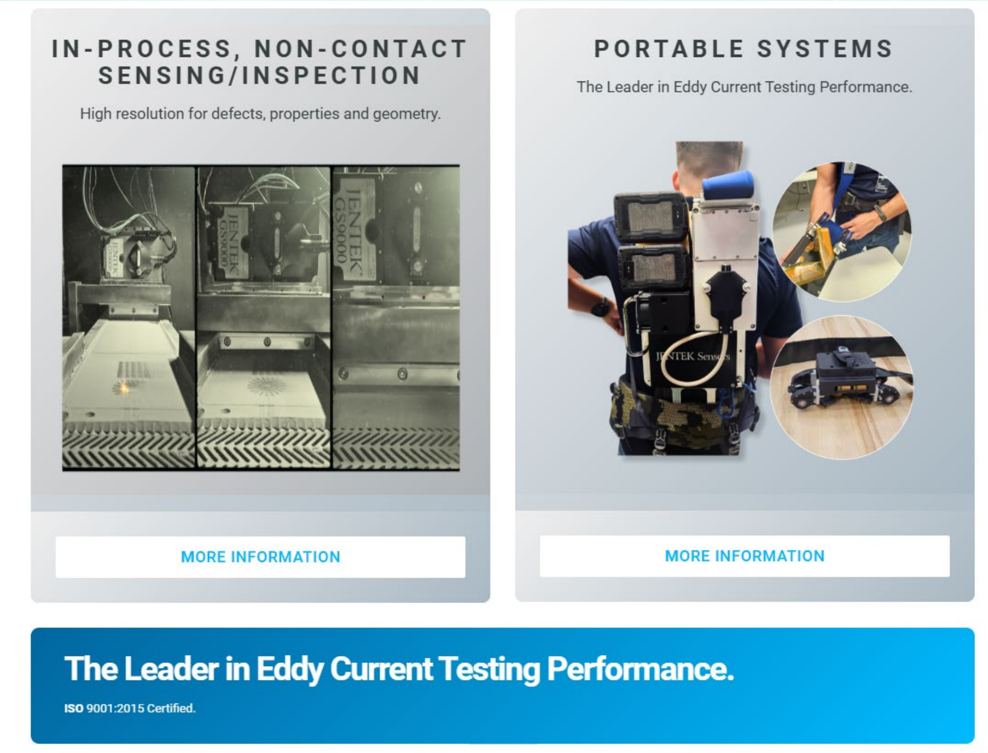
JENTEK Sensors, Inc. [+]

jentek@jenteksensors.com | neil.goldfineoverseas@jenteksensors.com

www.jenteksensors.com

University of Dayton Research Institute (UDRI) [*]

sara.Mirmasoudi@udri.edu | jessica.orr@udri.udayton.edu



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