In-Situ Sensing for Additive Manufacturing using Eddy Current Arrays

Neil Goldfine
September 28, 2026

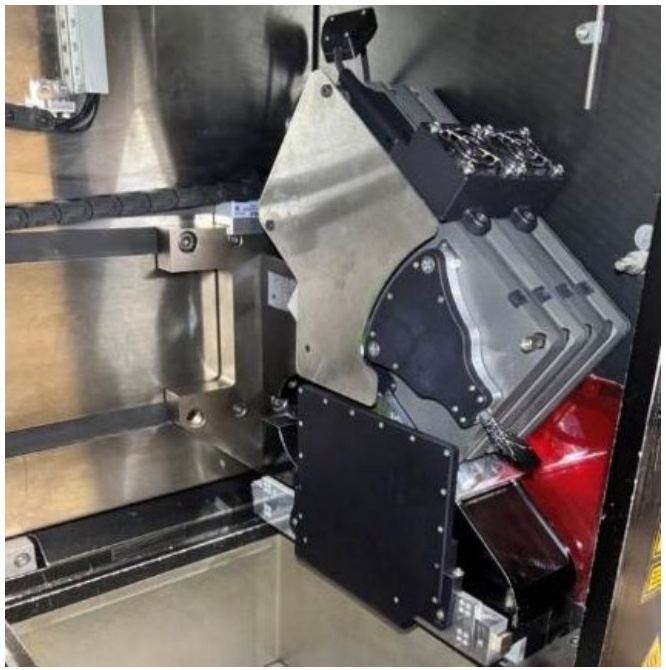
Co-Author: Andrew Washabaugh

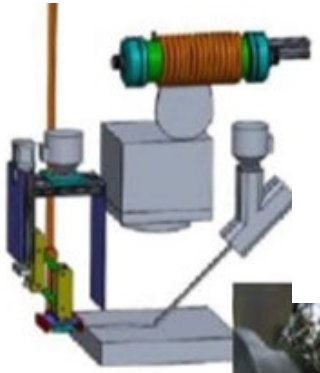
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andrew.washabaugh@jenteksensors.com

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LPBF





DED



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Abstract

This presentation summarizes recent advances and value offered by eddy current array sensing for metal additive manufacturing (AM). The value proposition for Laser Powder Bed Fusion (LPBF), Directed Energy Deposition (DED), and Additive Friction Stir Deposition (AFSD) is discussed. The challenges for each process are highlighted along with the current state of development. This includes the primary limitation of eddy current testing, which is the need for the sensor array to be near the inspected surface (e.g. within 1.5mm for LPBF and 5mm for DED/AFSD).

Data from recent demonstrations is provided along with near-term demonstration and development plans. Unique value of non-contact in-process (in-situ) eddy current arrays and specifically the MWM-Array variant of this technology are described for various quality assessment and control needs. These include property mapping, local defect detection (for both the current and prior processed layers, e.g. subsurface), surface and subsurface temperature measurement through conductivity estimation, and geometric imaging. Rapid data analytics, including opportunities for machine learning/AI is also discussed. Both layer-by-layer inspection and the potential for real-time control are discussed. The potential for machine agnostic qualification is also evaluated within the context of in-situ sensing.

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Topics Addressed

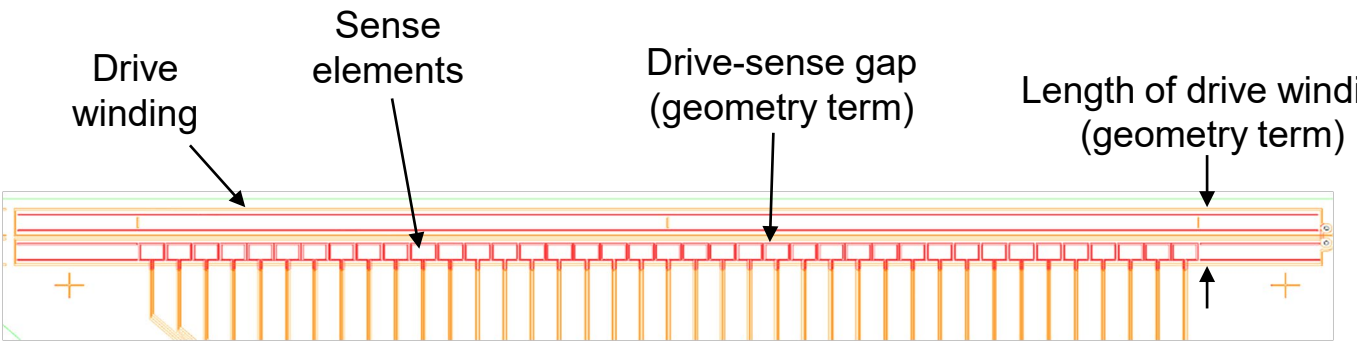
- **JENTEK Technology and Products**
  - Impedance Instrumentation
    - Fully Parallel Multiple Frequency Instrumentation for DED and AFSD
    - Next Generation Multiplex and Miniaturized for LPBF
  - Data Analytics Software
    - Air Calibration and Rapid Physics Software (Multivariate Inverse Methods, MIMs)
    - AI/ML (Tools & Model Training Services for Defects and Quality) (Use NG investor briefing slides)
    - Automation Module for Integration (get from MW)
  - Engineering Services for Integration Support
- **Laser Powder Bed Fusion (LPBF) in-situ Eddy Current Array Layer-by-Layer Sensing & Inspection**
  - EOS M290 Data (with CCAM)
  - Dart 2 Data (with UDRI)
  - GE Concept M2 Data
  - CCAM Desktop NDT on LPBF Parts with JENTEK MWM-Array
- **Directed Energy Deposition (DED)**
  - Layer-by-Layer Near Real-Time Sensing & Inspection
  - Real-Time Following (and leading) for Qualification and Control
- **Additive Friction Stir Deposition (AFSD)**
  - Layer-by-Layer Near Real-Time Sensing & Inspection
  - Real-Time Following (and leading) for Qualification and Control
- **Fatigue Test Monitoring for AM Parts**

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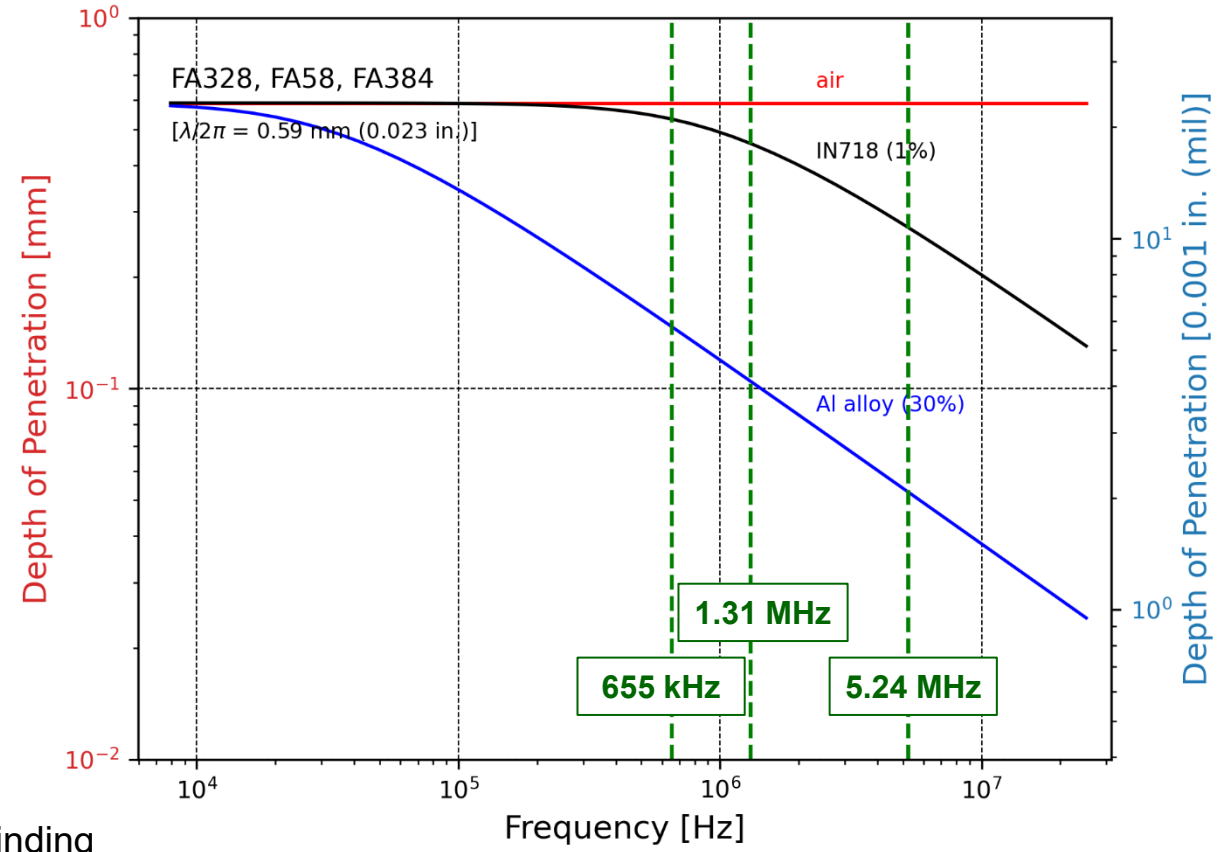
MWM-Array Eddy Current Background

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



Example Eddy Current Array (MWM-Array)

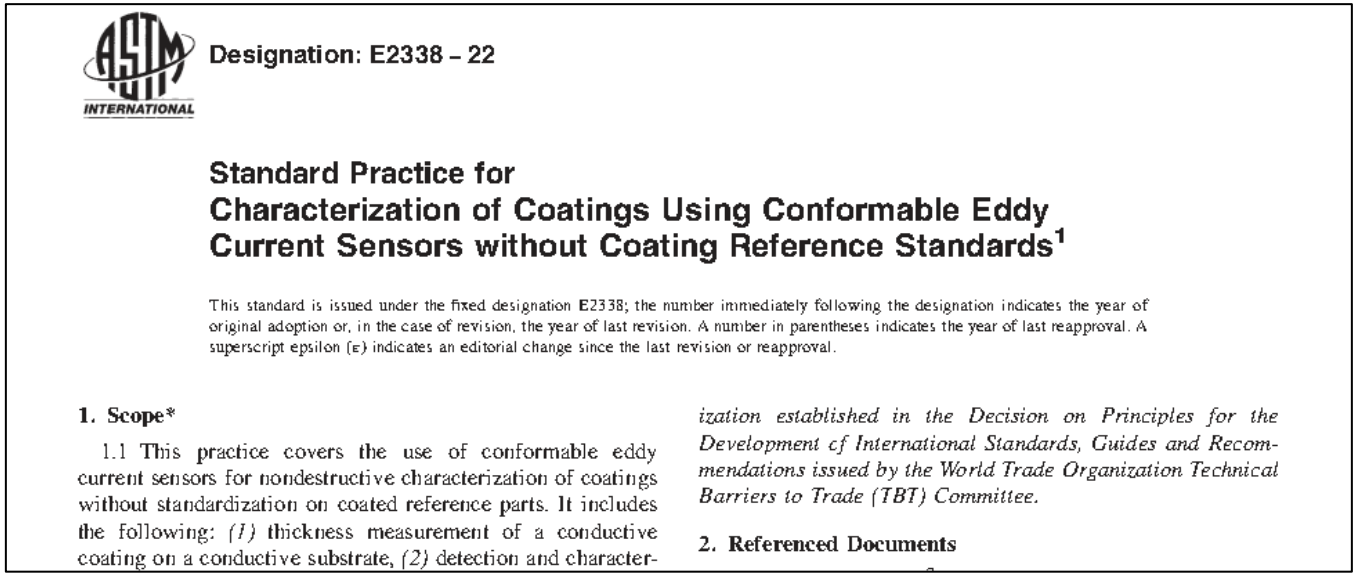


Affects the lift-off that can be tolerated

Primary factor affecting field penetration into the metallic material under test

Relevant Eddy Current Standards

- 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)



Designation: E2338 – 22

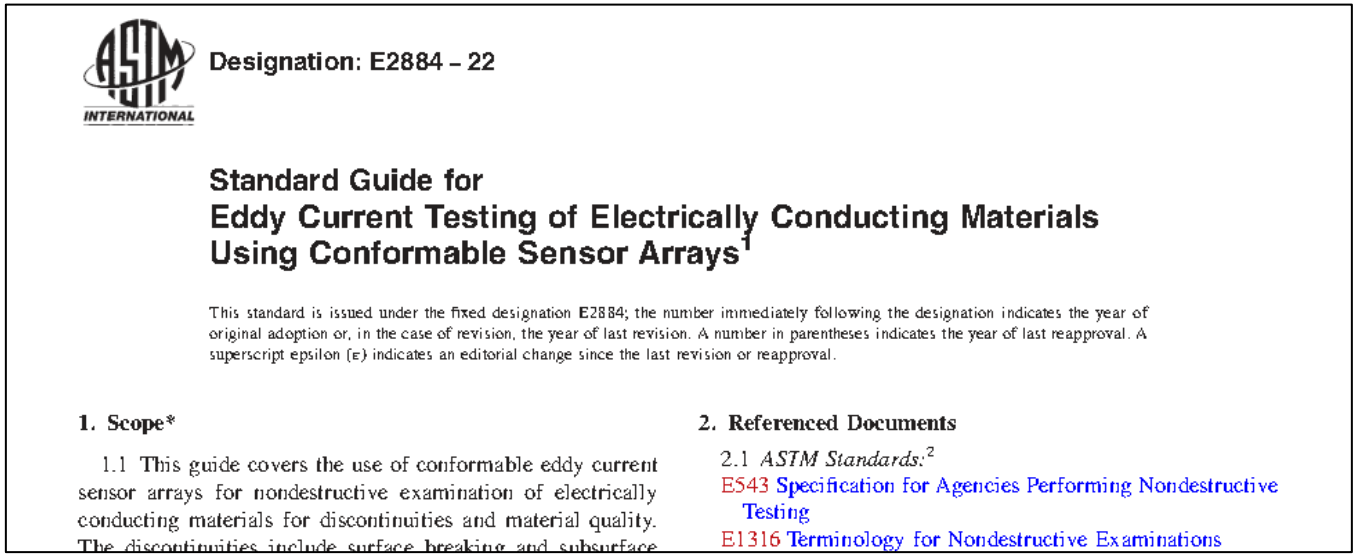
Standard Practice for
Characterization of Coatings Using Conformable Eddy Current Sensors without Coating Reference Standards[1]

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 characterization 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



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

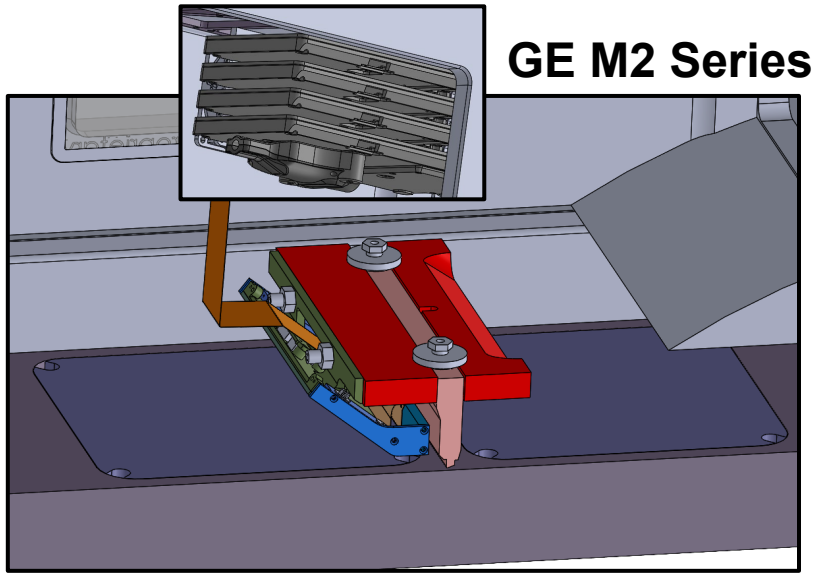
2. Referenced Documents

2.1 *ASTM Standards:*[2]

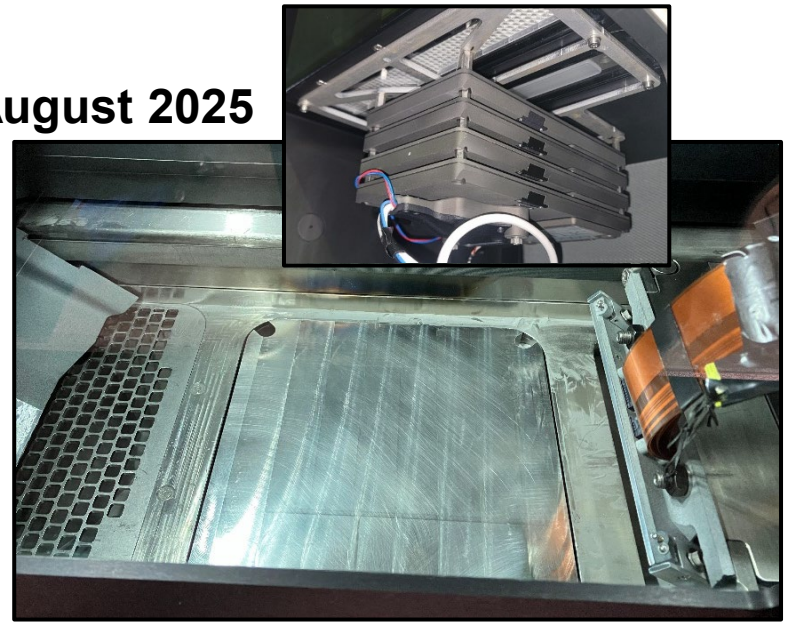
E543 Specification for Agencies Performing Nondestructive Testing

E1316 Terminology for Nondestructive Examinations

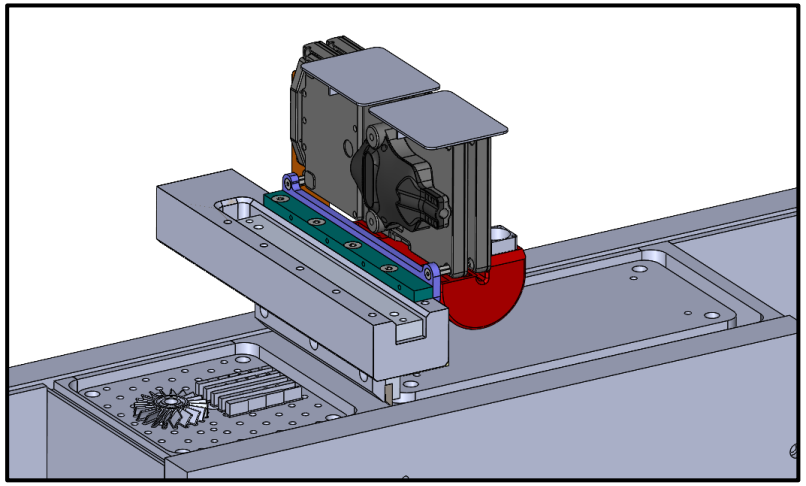
Example 2025 & 2026 GS9000 LPBF Installations / Demonstrations

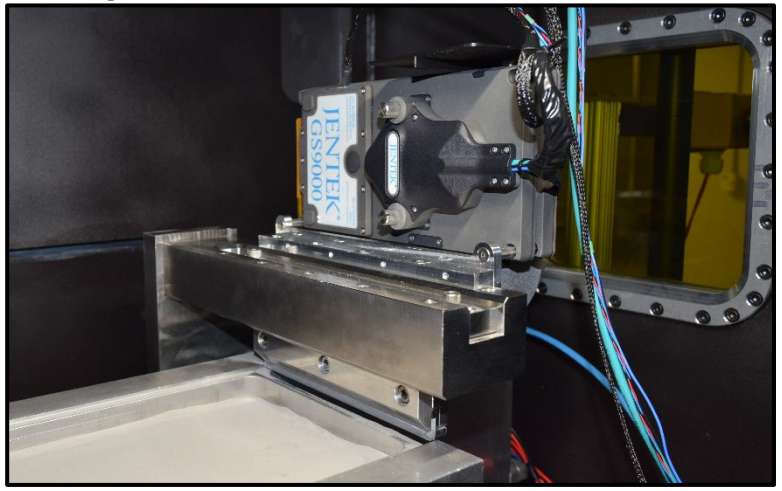


GE M2 Series 5 – August 2025

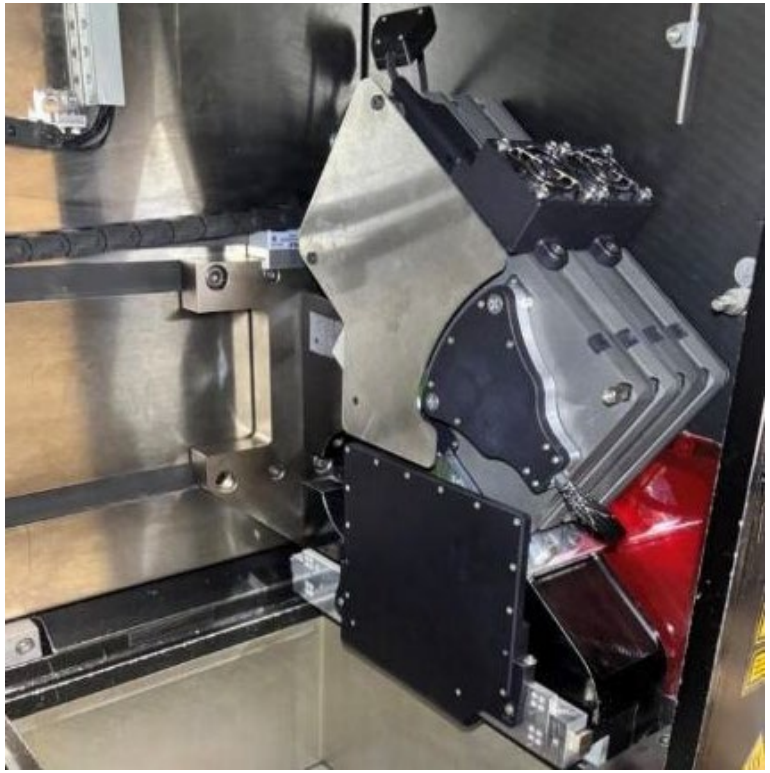


UDRI DART 2 – February 2025





EOS M290
CCAM 2026



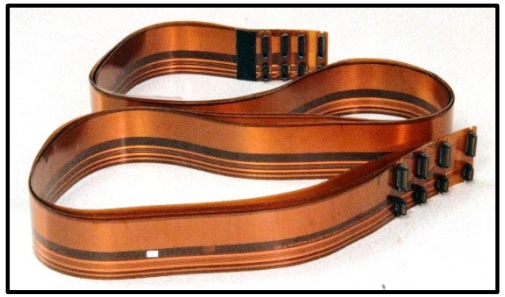
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GE M2 Series 5 Installation Components

GS9000 Board Stack



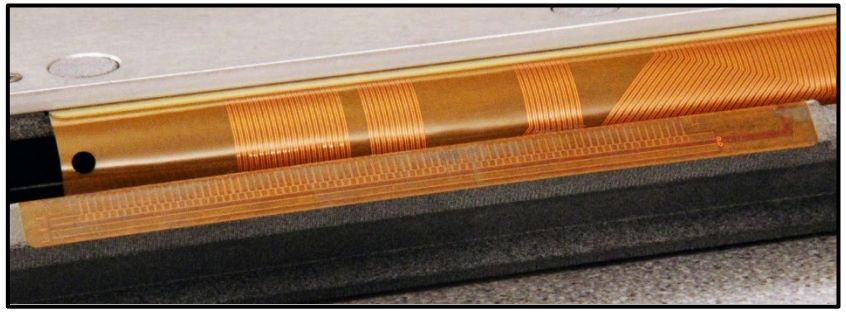
Flex Cables (optional)



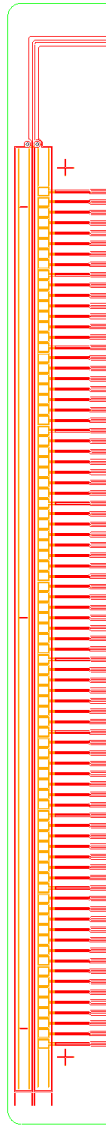
Sensor Mount Kit



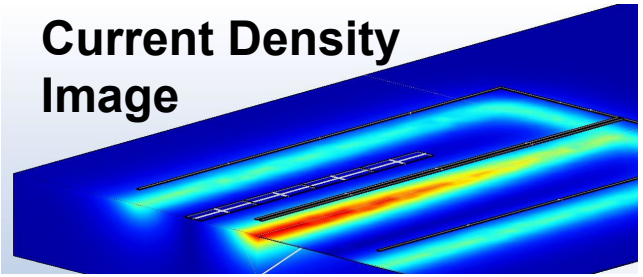
Mounted 79-Channel MWM-Array



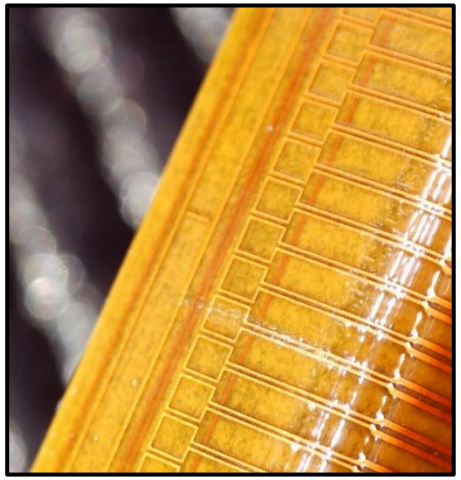
MWM-Array Schematic, with Dual-Rectangle Drive



Current Density Image



MWM-Array Photo, with Dual-Rectangle Drive



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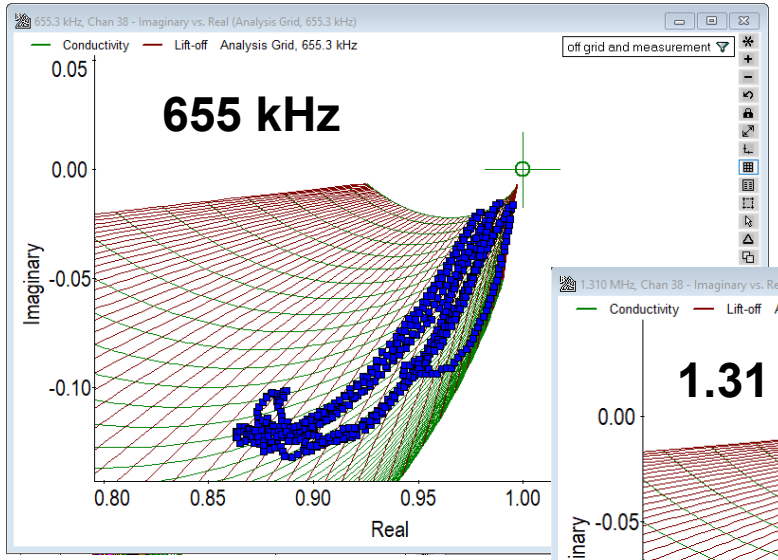
LPBF MWM-Array Technology Advantages

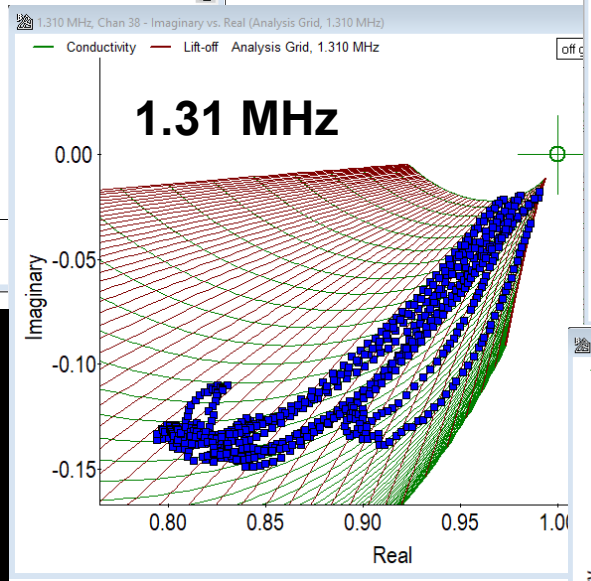
1. Conductivity and Prior Layer height Imaging (with Air Calibration)
   - Sensor response independent of sensor temperature
   - Wide conductivity range and multiple frequency capability
   - Air calibration (ASTM E2338)
2. Surface and Subsurface defect detection (with ML/AI)
   - Extremely reproducible data enables intelligent filtering
   - High resolution array (0.03 or 0.04 inch sensing element width)
   - Three frequencies simultaneously
3. Sub-pixel geometric imaging (with ML/AI)
4. *Real-time control/rapid data processing*

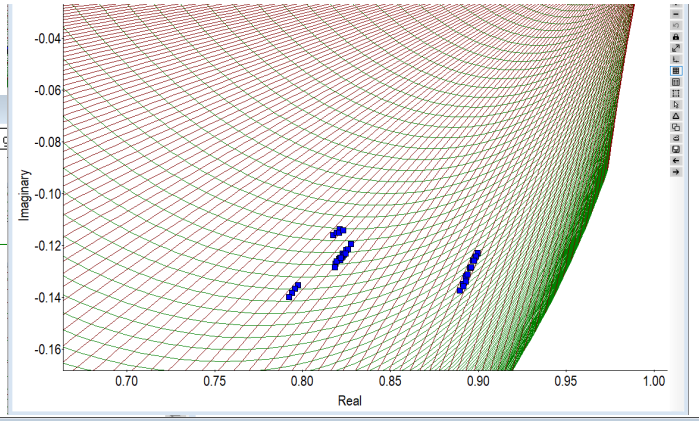
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Multifrequency Conductivity Measurement with Automatic Lift-off Correction

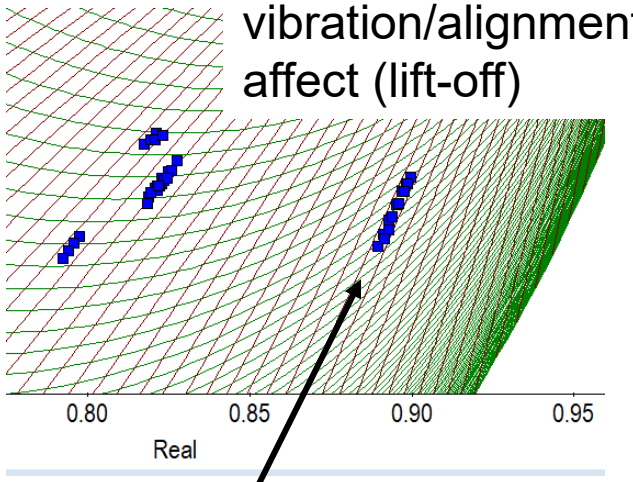
- Patented Air Calibration Methods
- Independent measurement of conductivity and lift-off
- Re-calibration layer-by-layer (optional)

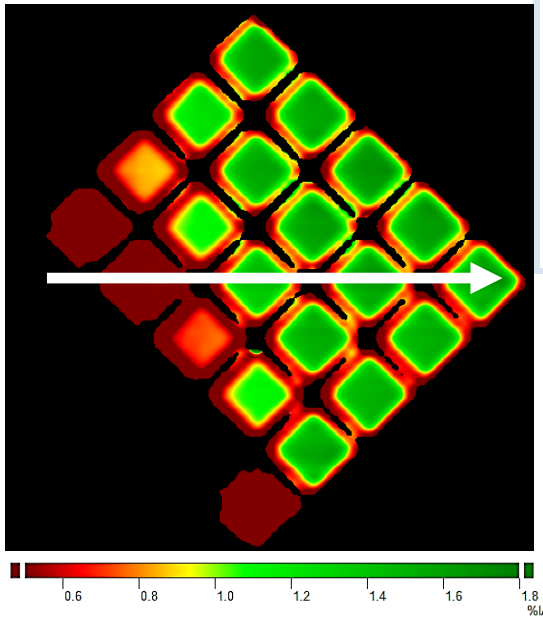


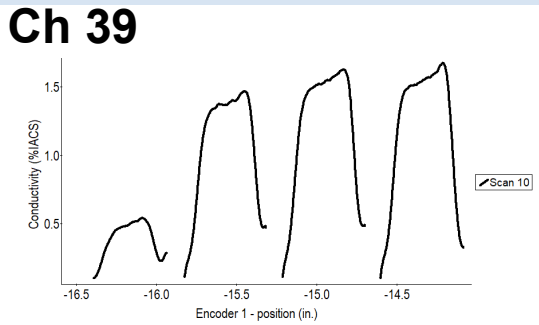


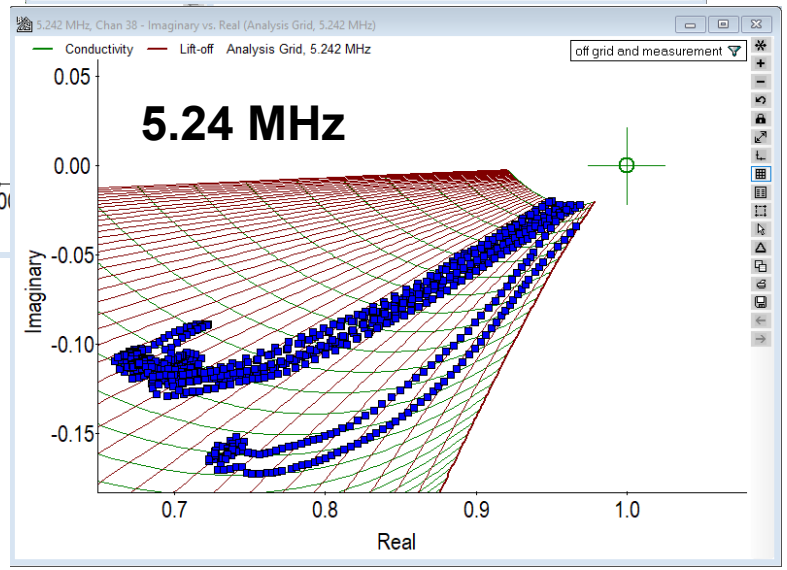


Recoater vibration/alignment affect (lift-off)









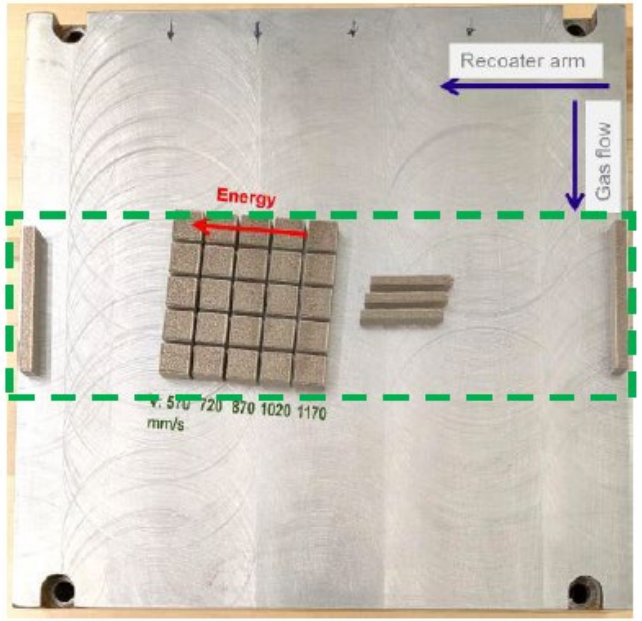
- Lift-off impact automatically removed
- Defect response automatically rescaled for lift-off

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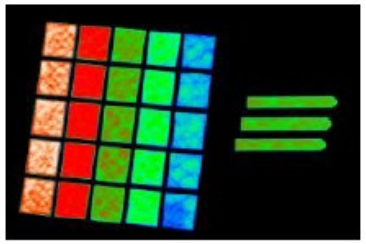
CCAM Results for layer height (liftoff) imaging using MWM-Arrays

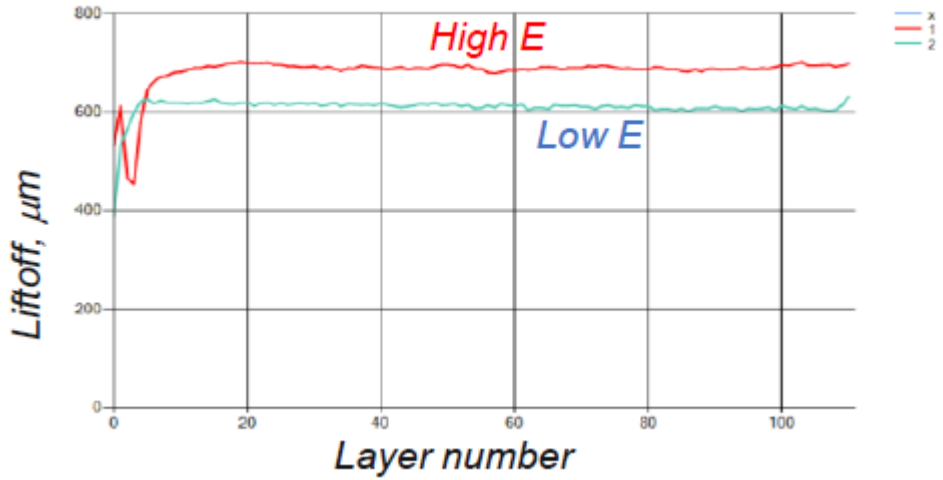
Data from CCAM

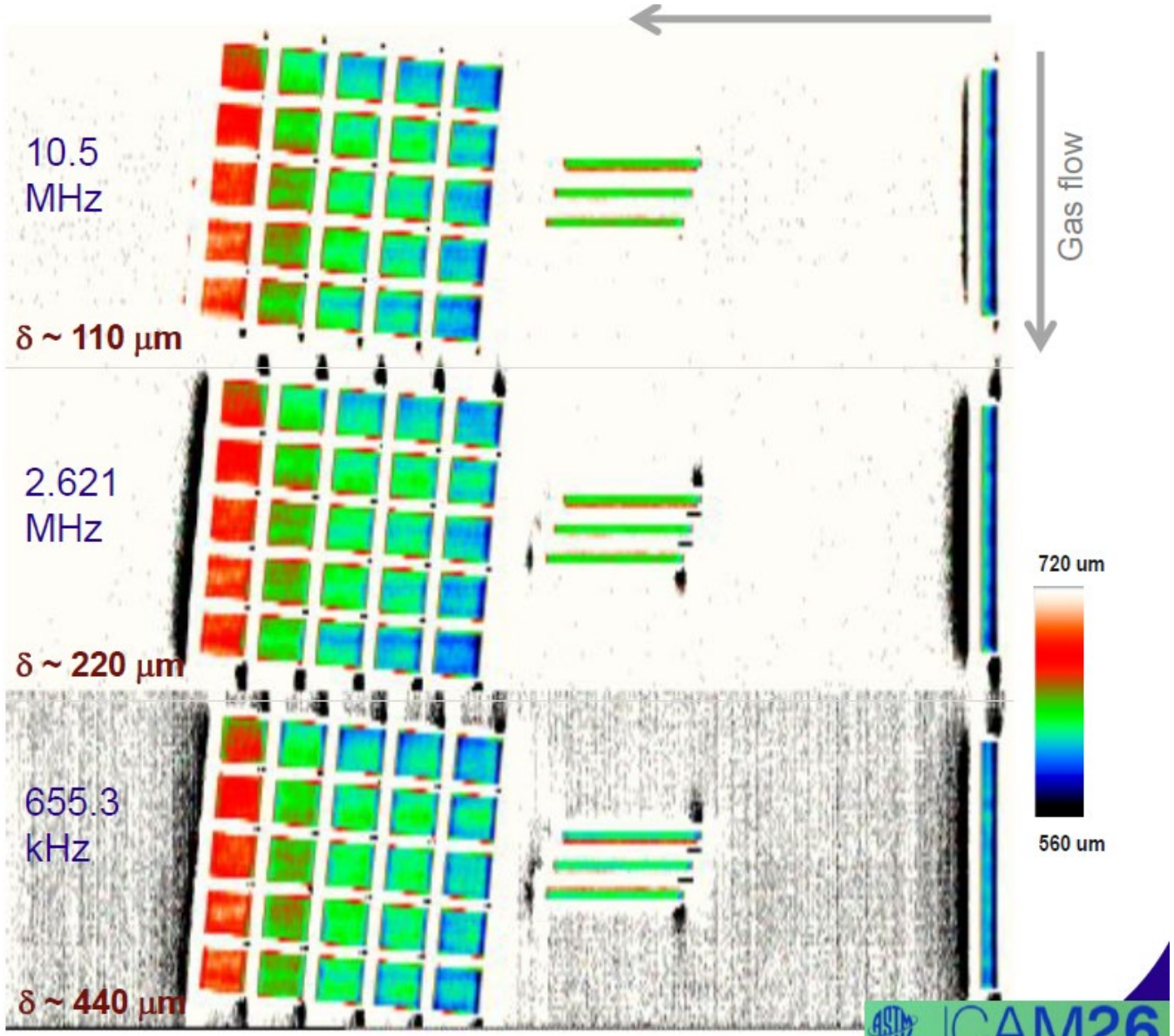
Test build:



NIR map:
(Energy density)







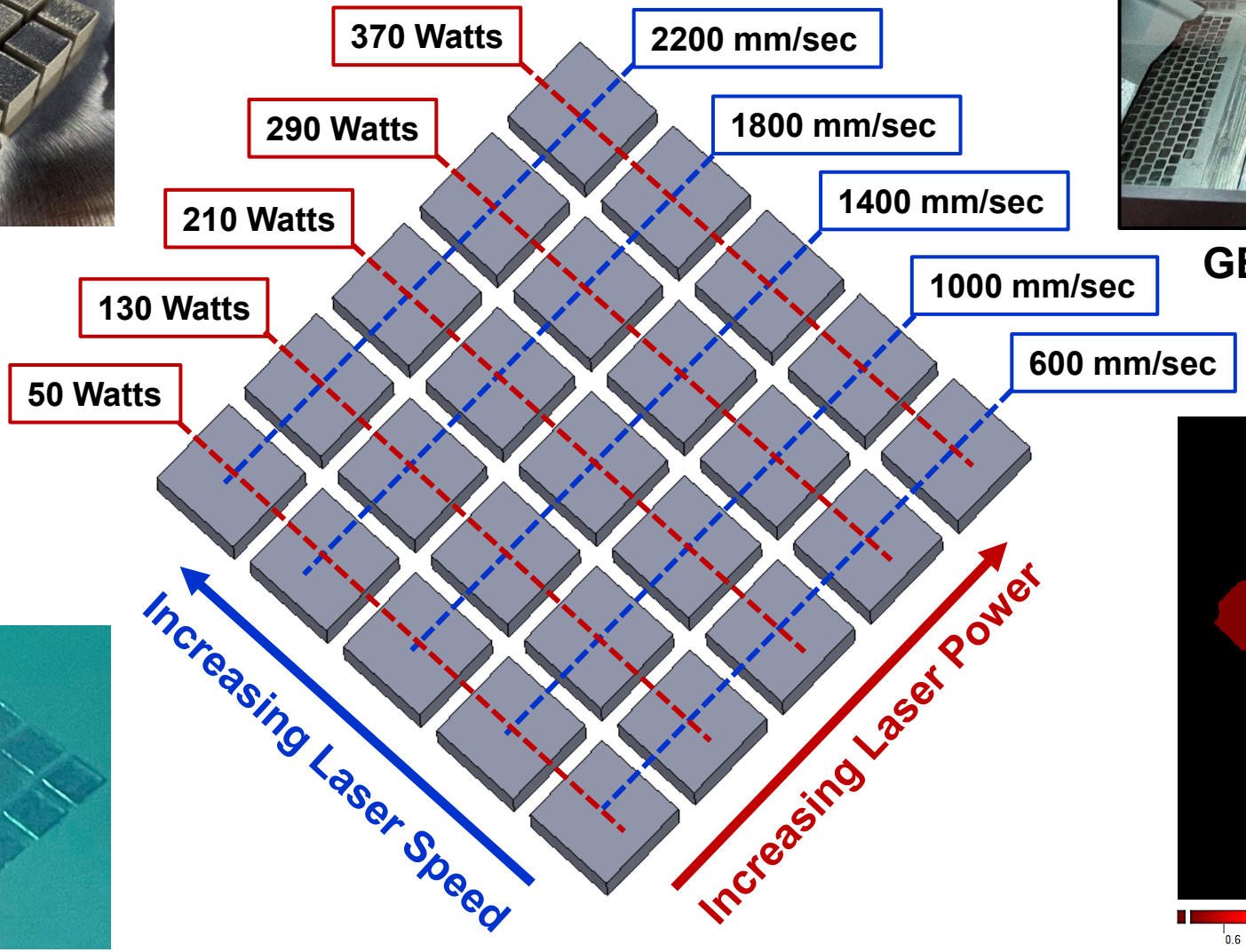
ICAM26

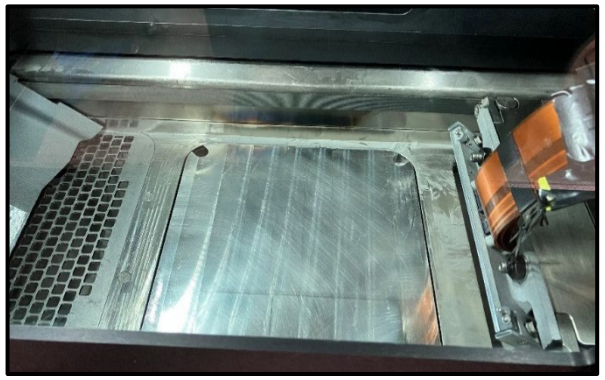
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Conductivity Mapping (Varied Laser Power and Speed)



Photo



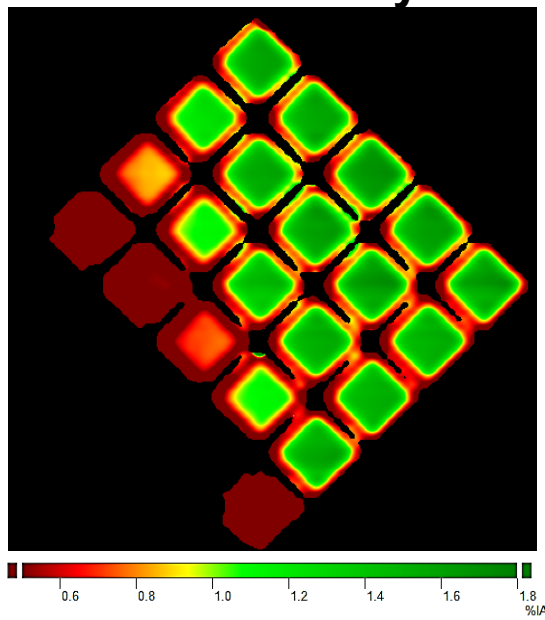


GE M2 Installation

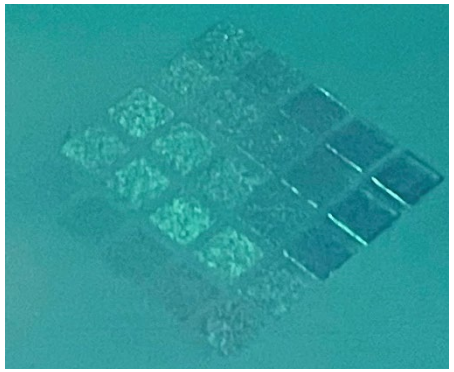


MWM-Array

Conductivity

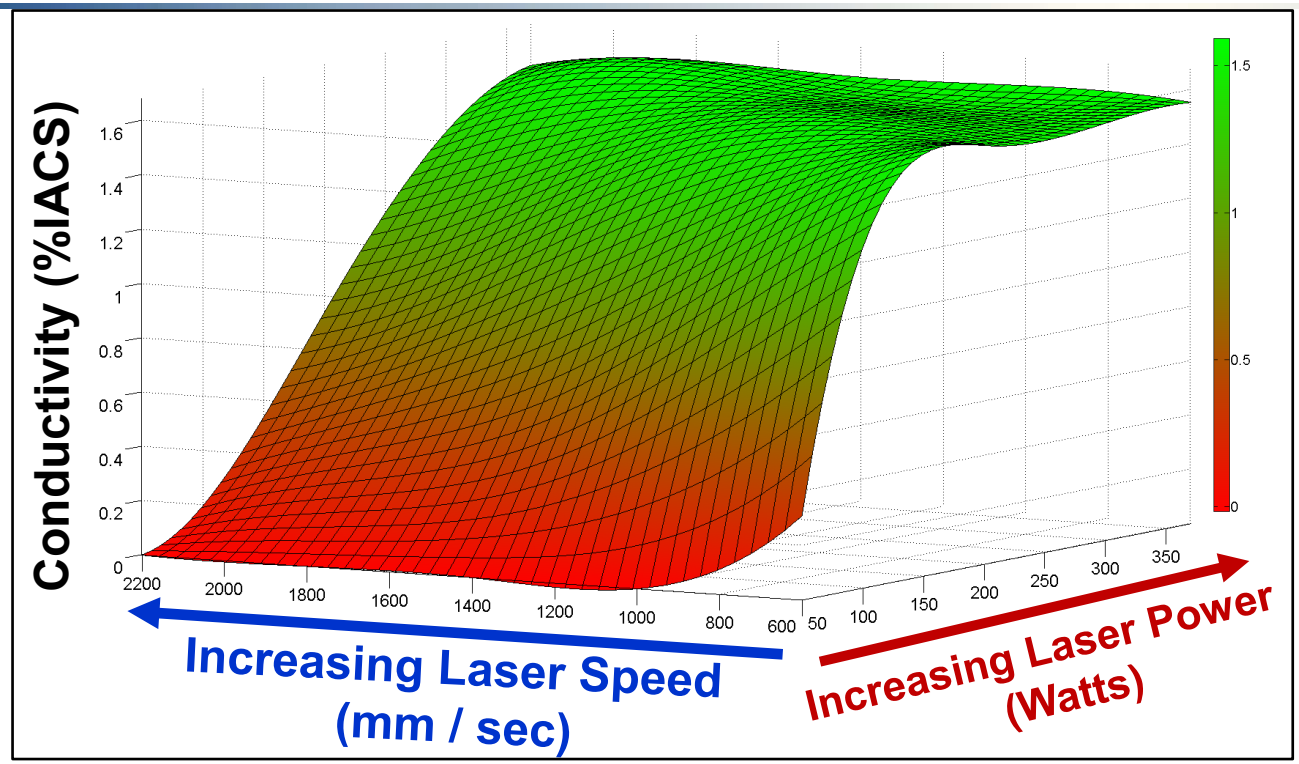


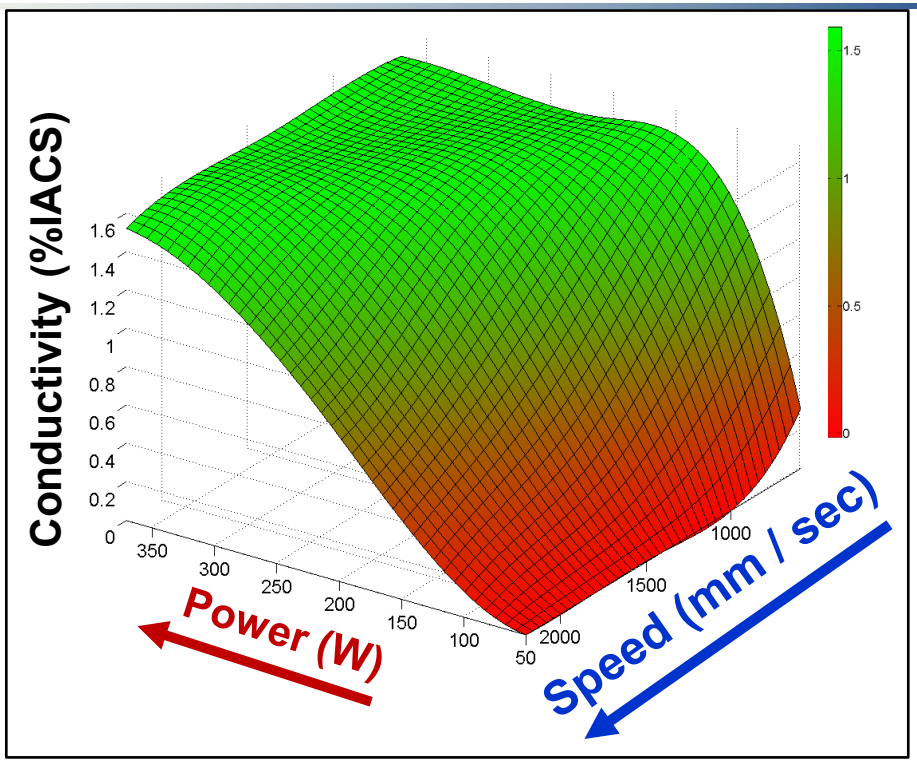
Photo

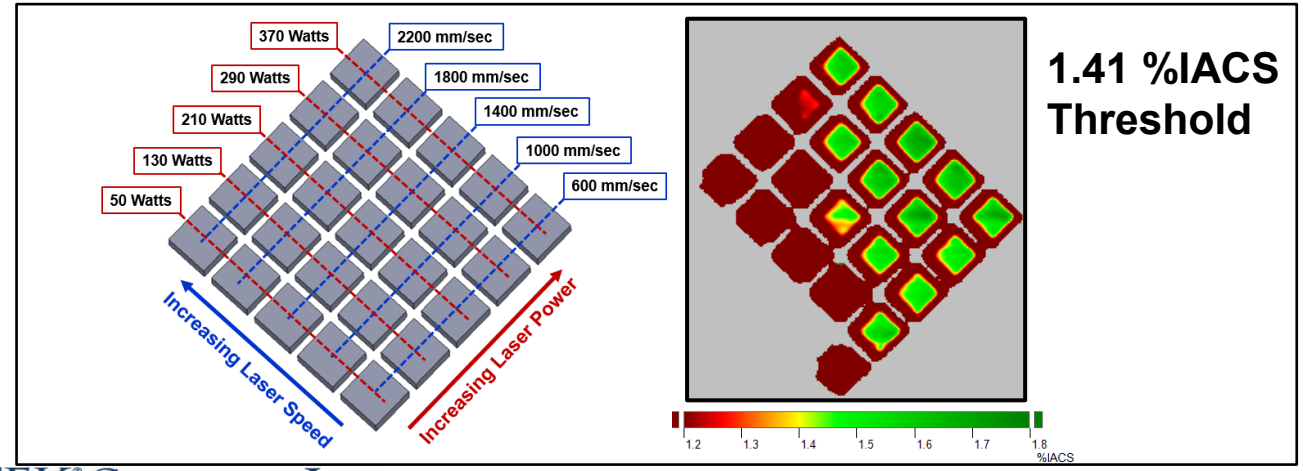


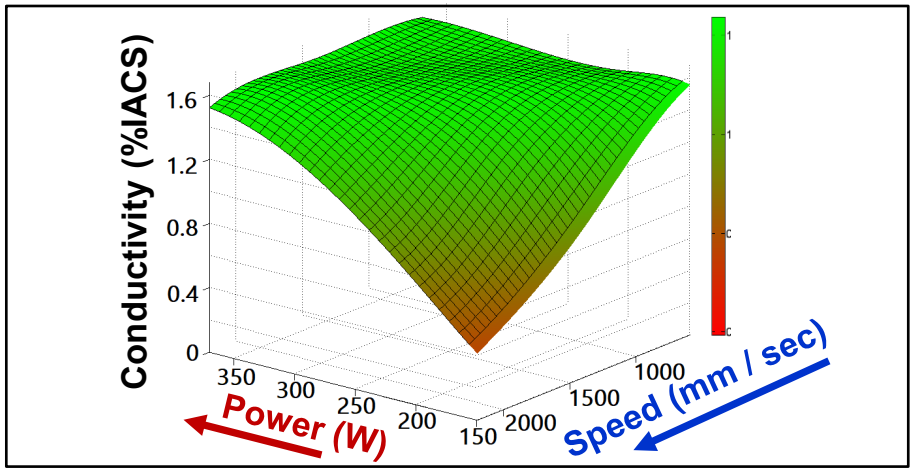
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Conductivity Surface by Laser Parameters



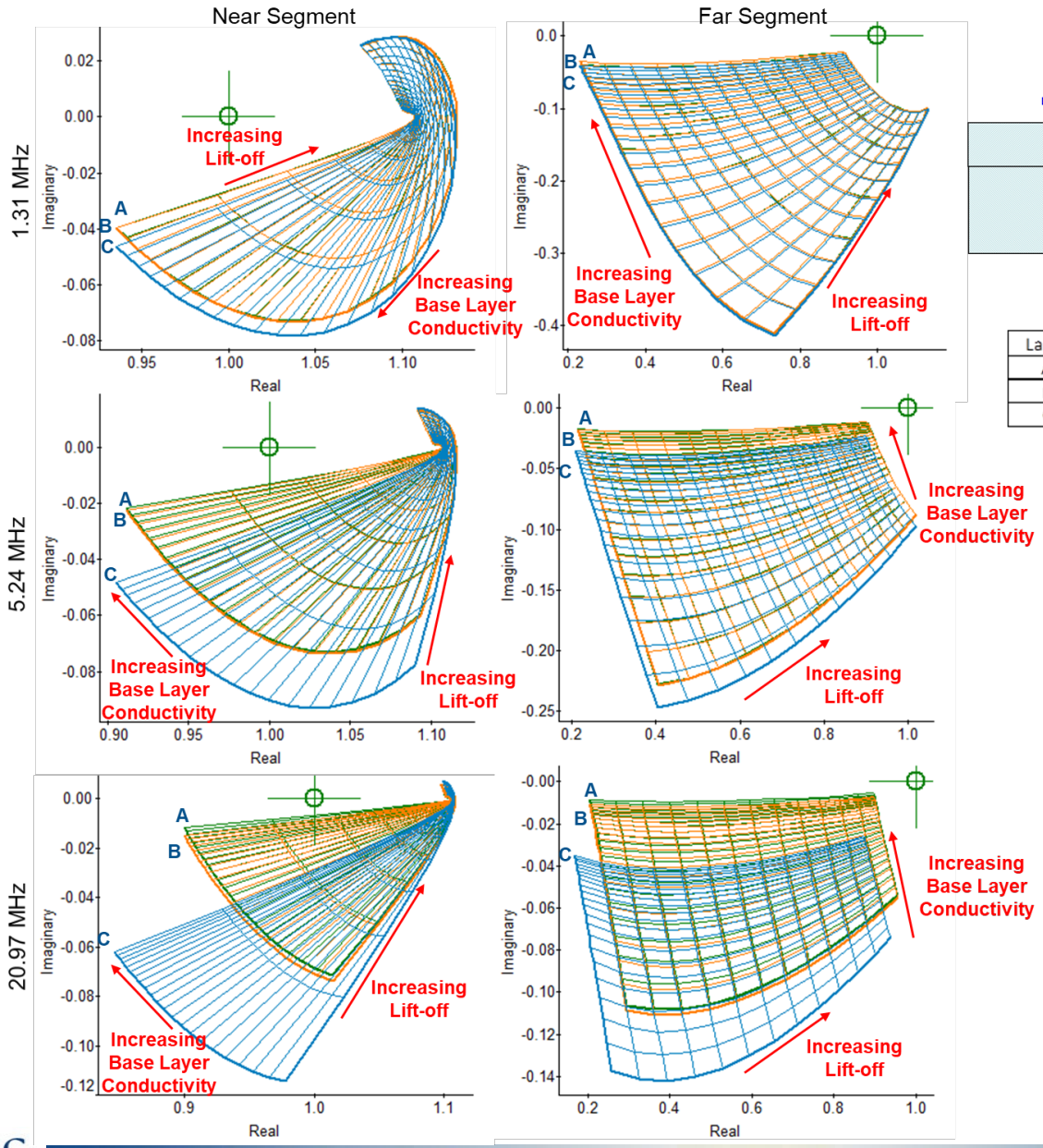


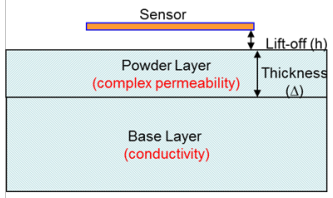




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Measurement Grid Methods (Nonferrous)





Label	Color	Powder
A	Green	Air
B	Orange	Titanium
C	Blue	Aluminum

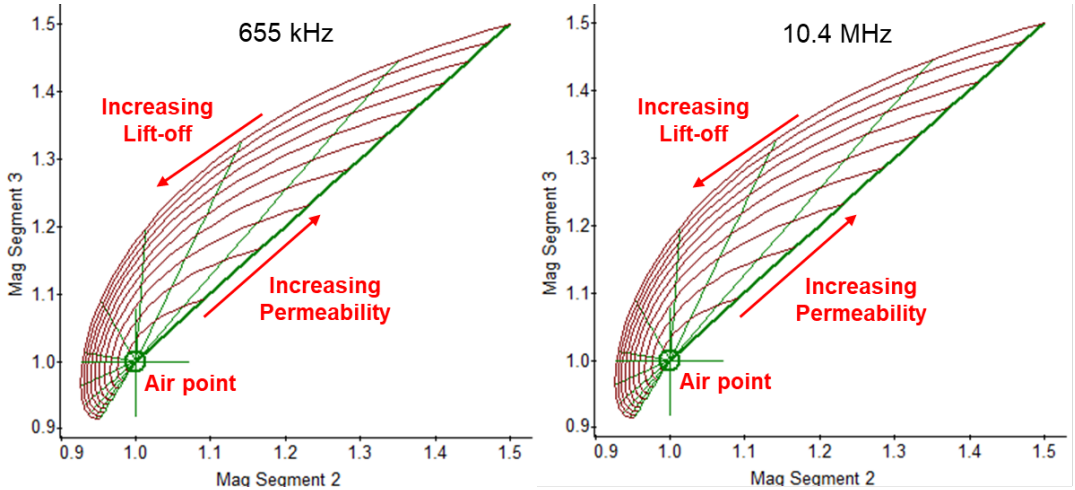
Segmented sensor grids for estimation of base material conductivity through a powder layer

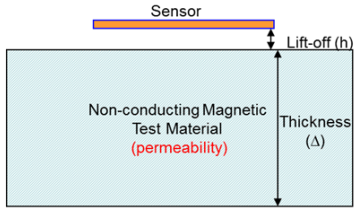
Complementary information between frequencies and segments

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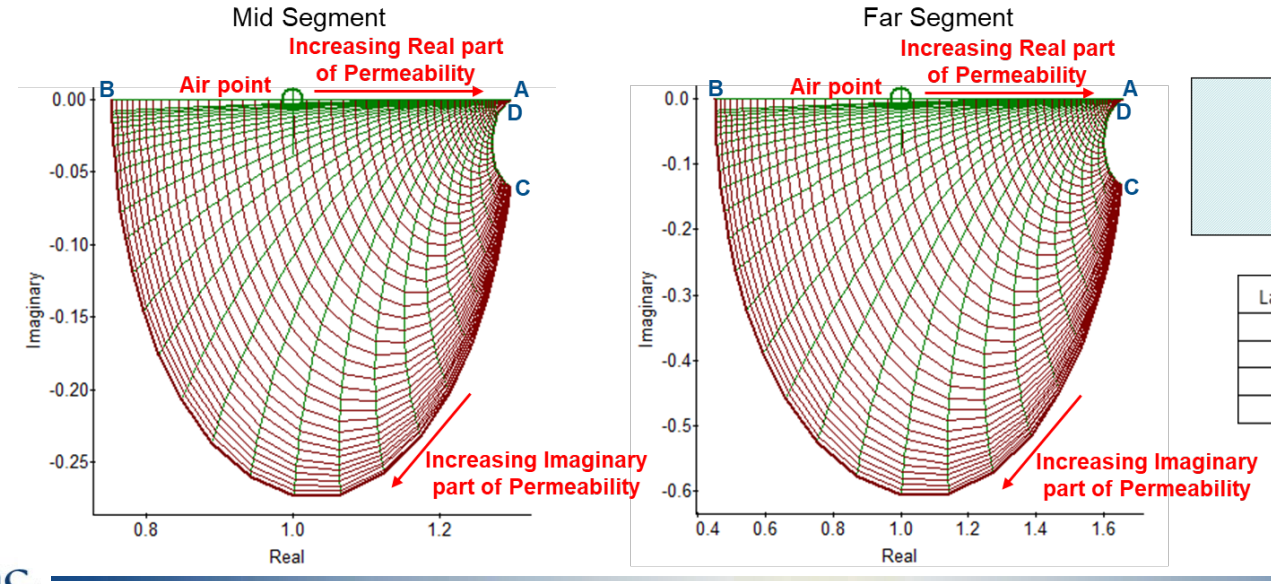
Ferrous Metal Measurement Grid Methods (Permeability & Lift-off)

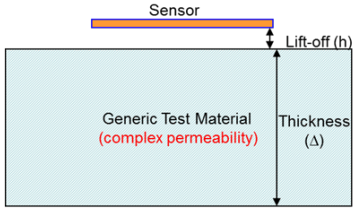
Segmented sensor grids for estimation of permeability and lift-off





Complex mu – halfspace, 0.020 in. lift-off, FA294



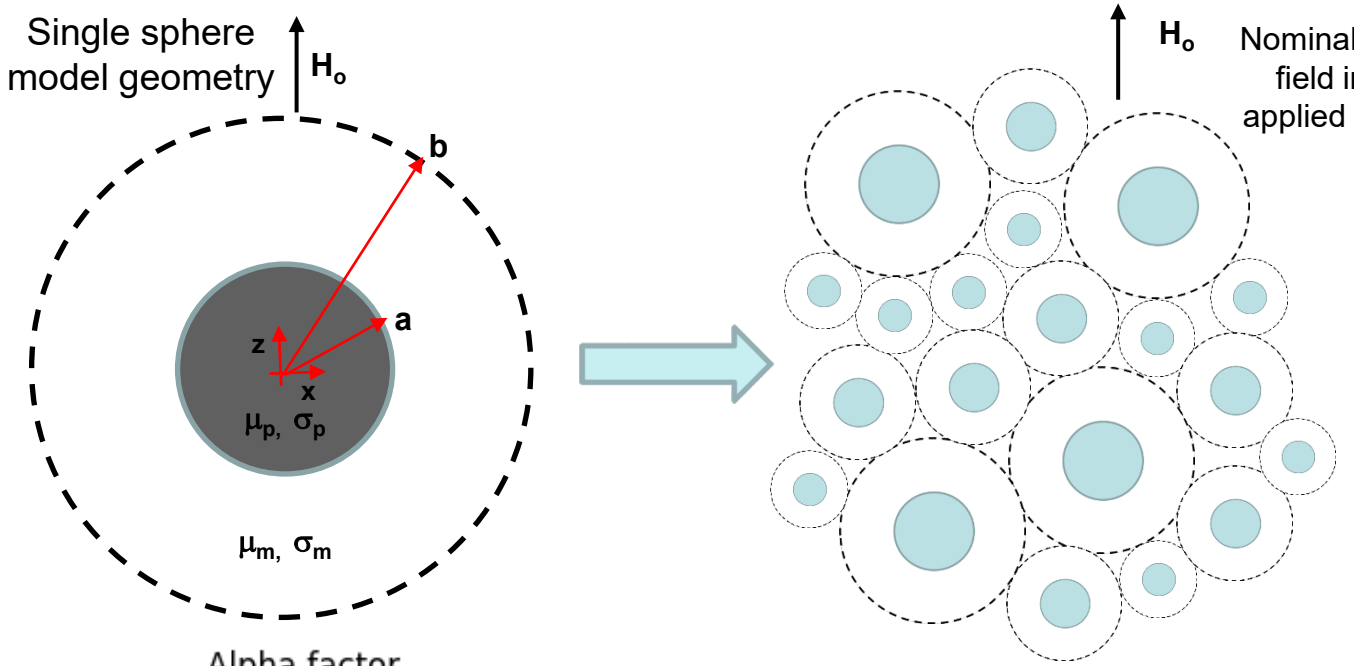


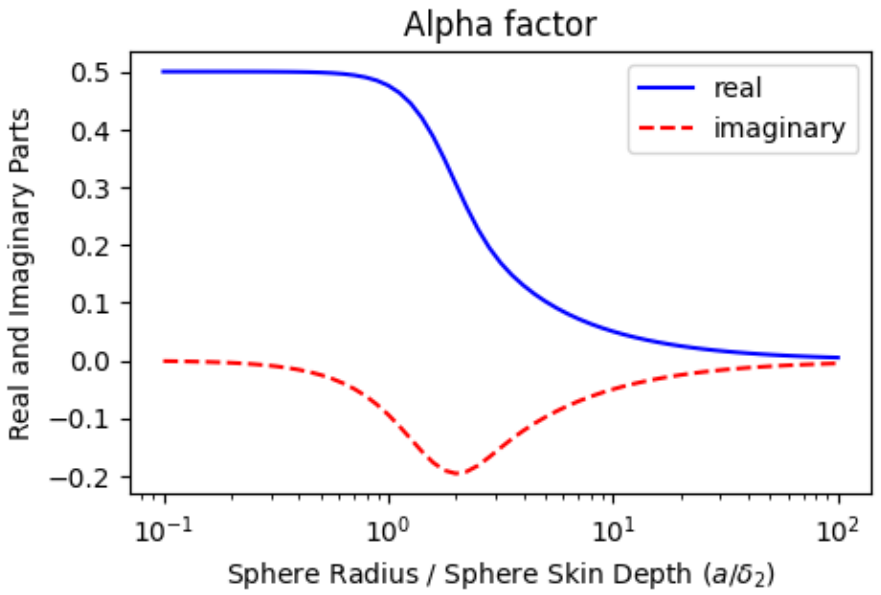
Label	μ_{real}	μ_{imag}
A	1000	0
B	0.1	0
C	0.1	-10
D	1000	-10

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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

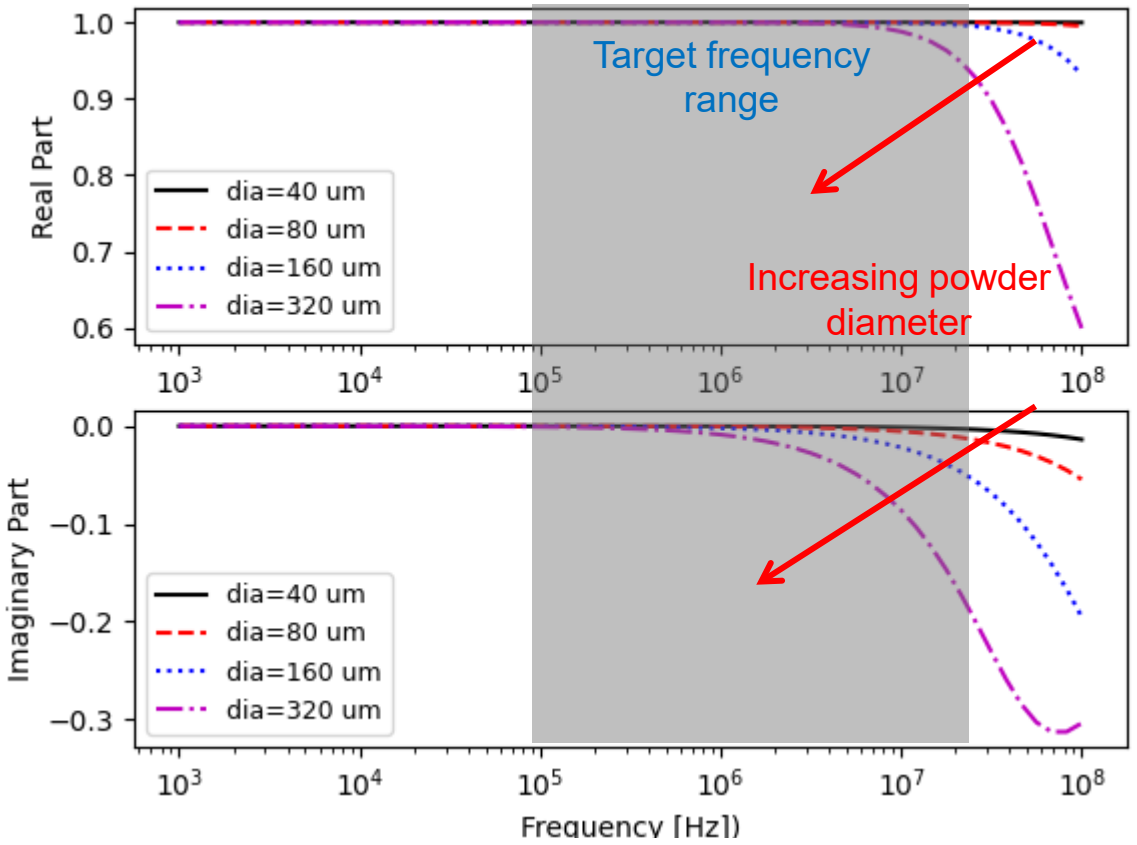
Powder (μ'_r, μ''_r, σ)

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

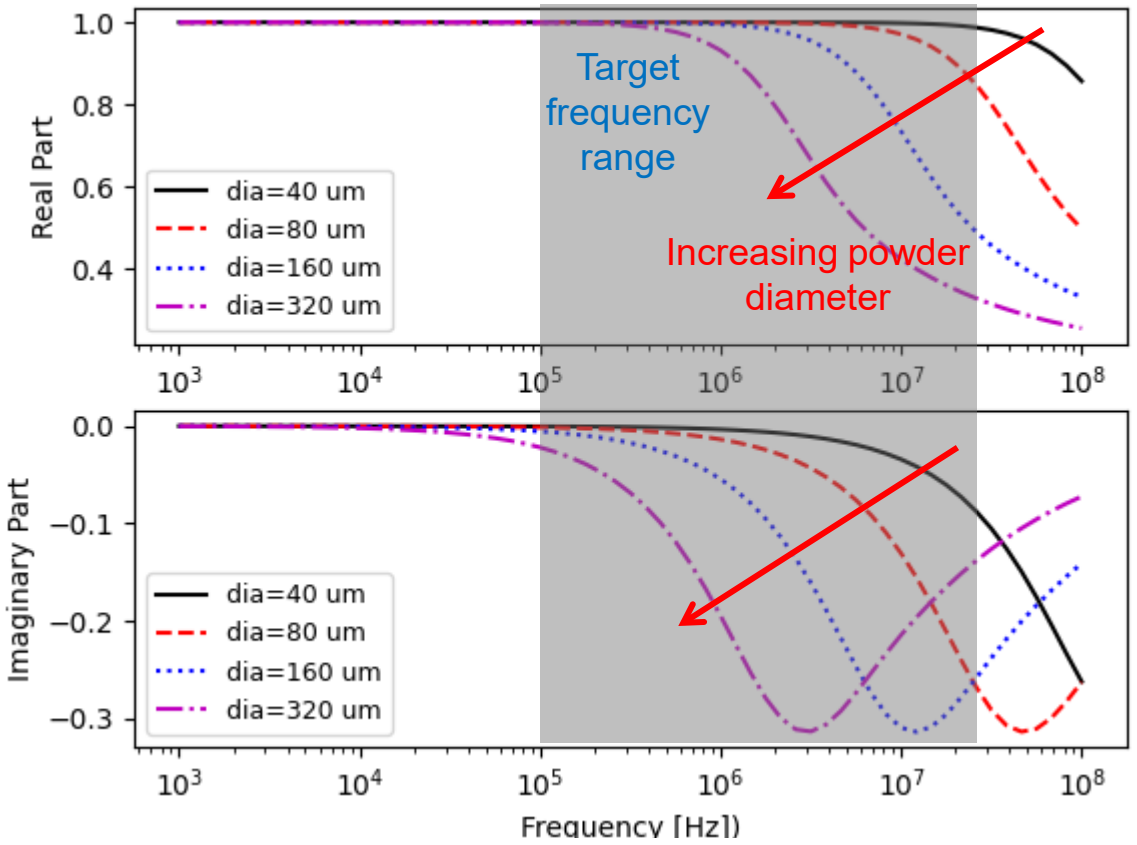
Powder Model (2)

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

Nickel alloy (and similar) (1%IACS), Vol. frac. = 0.75

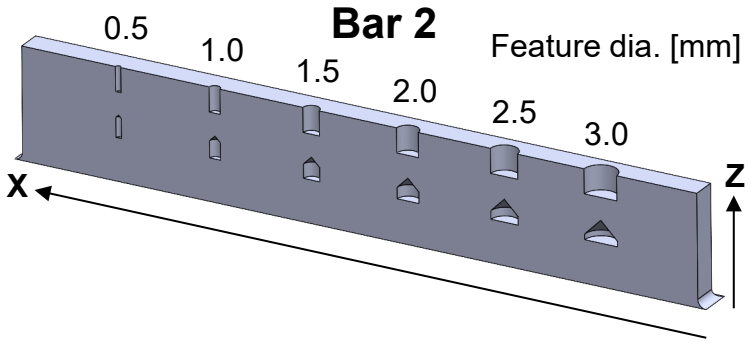


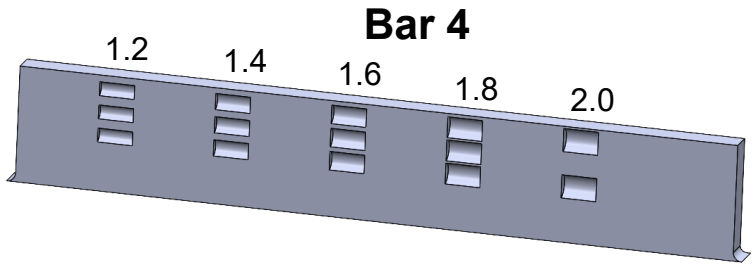
Aluminum alloy (25%IACS), Vol. frac. = 0.75



UDRI DART 2 Void Detection/Imaging Example

- Example Vertical Slices (x-z plane)

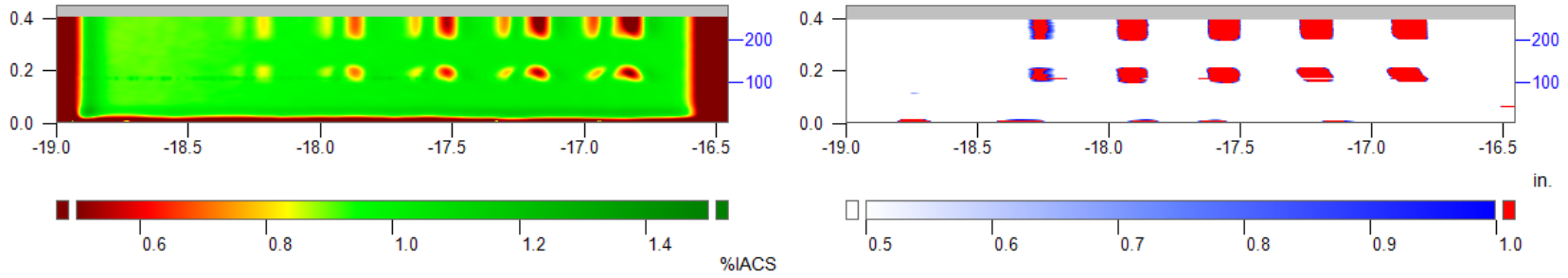




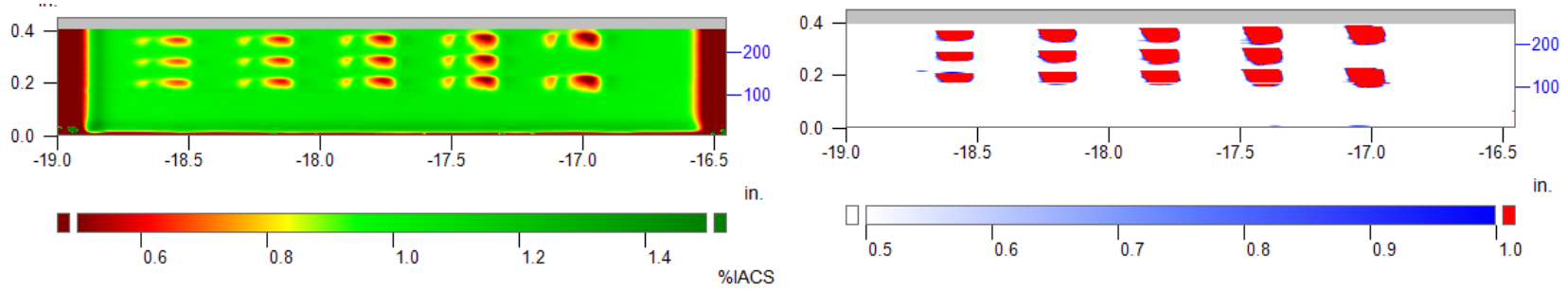
Effective Conductivity

Machine Learning Using Simple Shape Filter (5 MHz only)

Bar 2 (Chan 29)



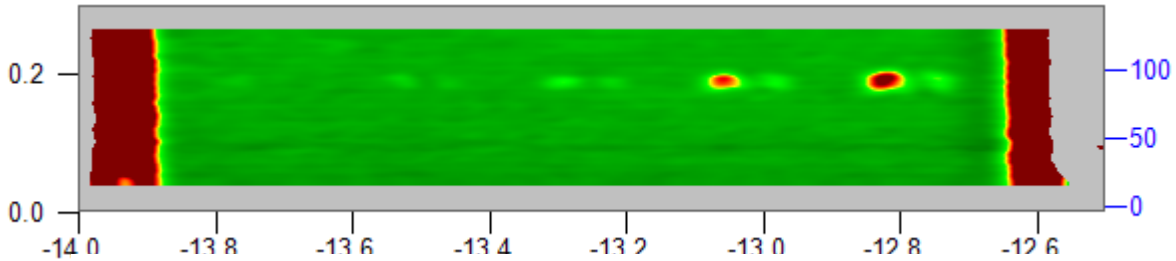
Bar 4 (Chan 15)

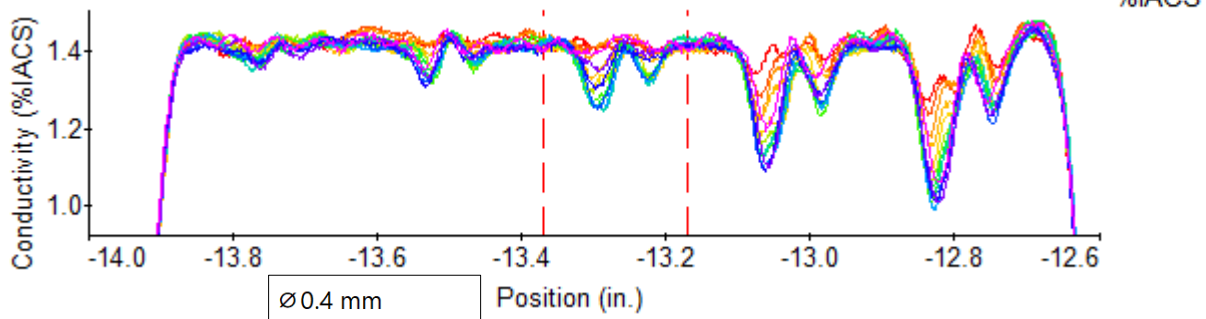


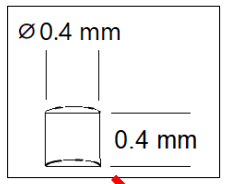
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Astro Build 3 Void Detection/Imaging Example

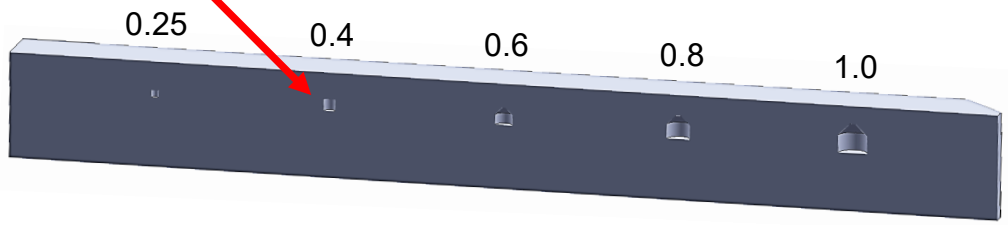
Effective Conductivity







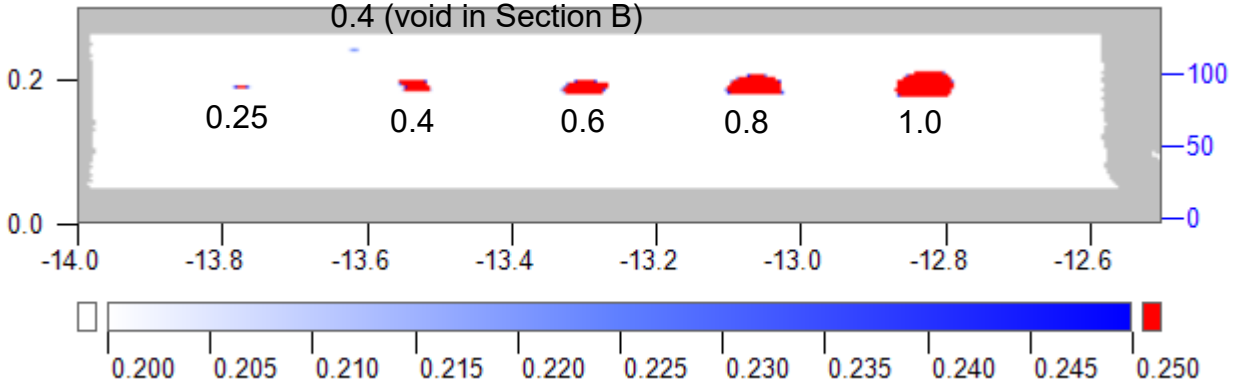
Bar 2: larger voids have chamfered tops
Void dia. and total height. [mm]

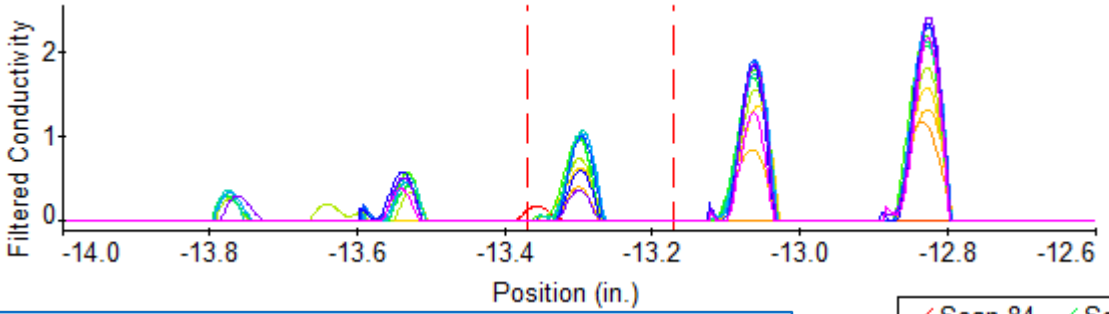


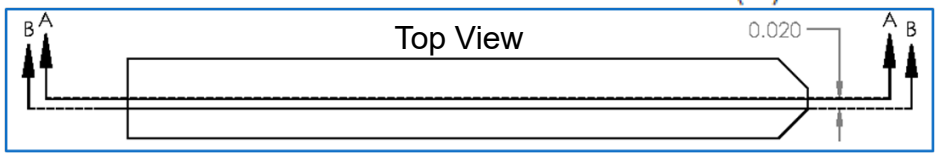
Section A

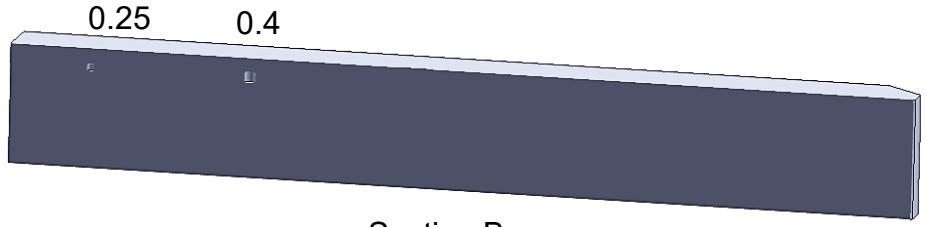
Simple Shape Filter (5 MHz only)

0.4 (void in Section B)

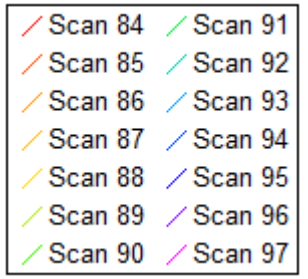






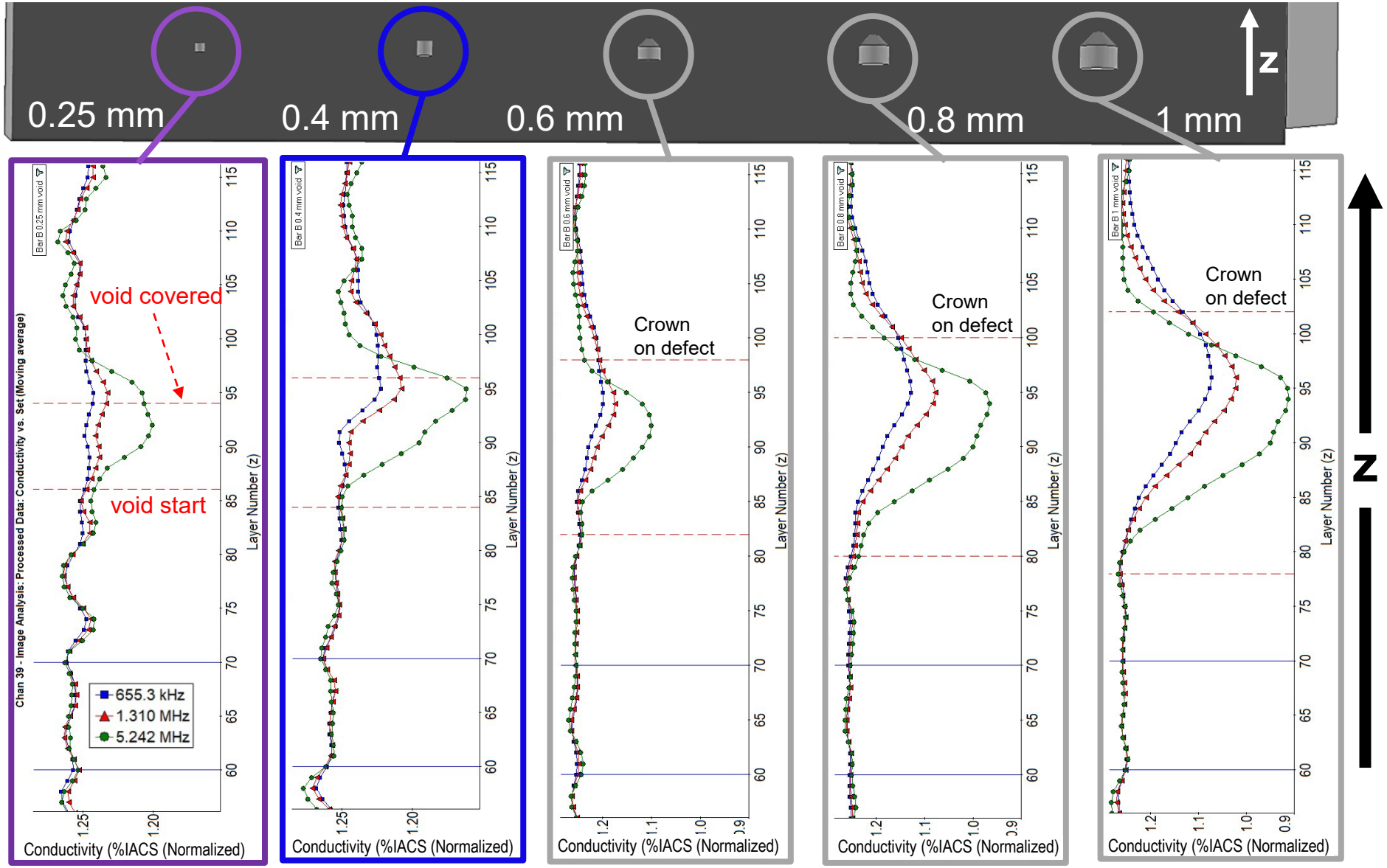


Section B

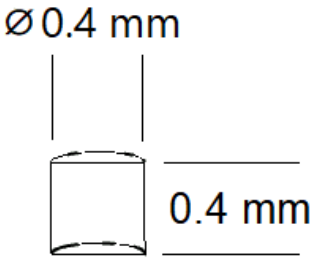


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Subsurface Void Detection



Pill-box shaped voids

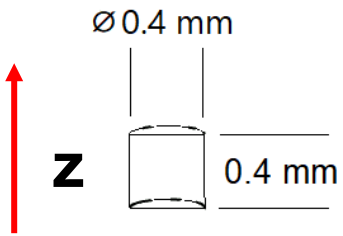


2pt z-direction moving average applied to this data

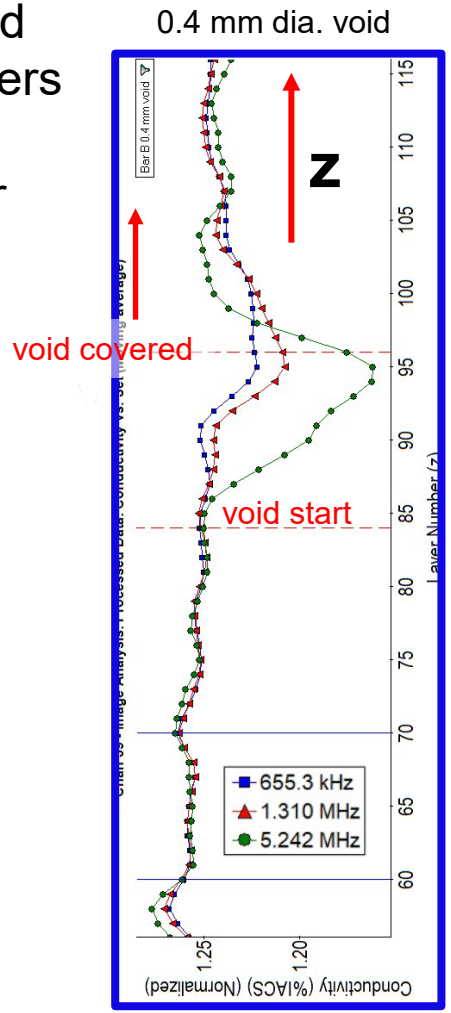
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Covered Void Detection / z-Directed Visualization

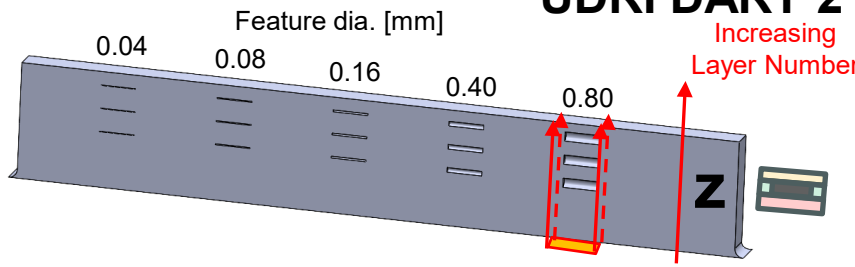
Unique capability to detect covered defects 4-10 layers below current processing layer

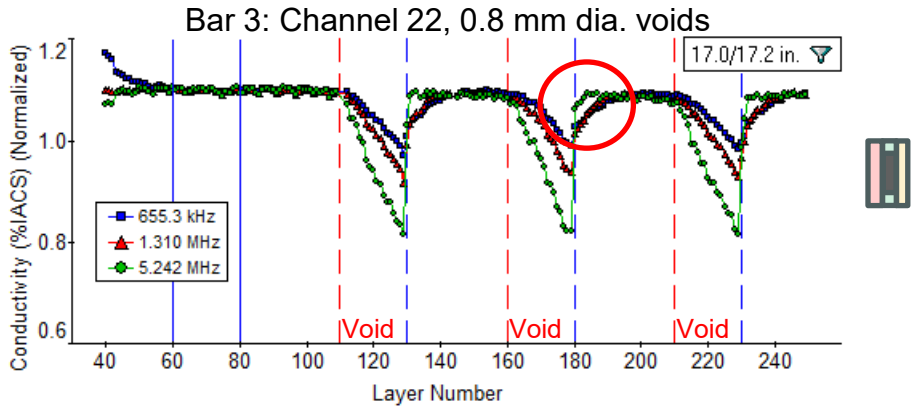


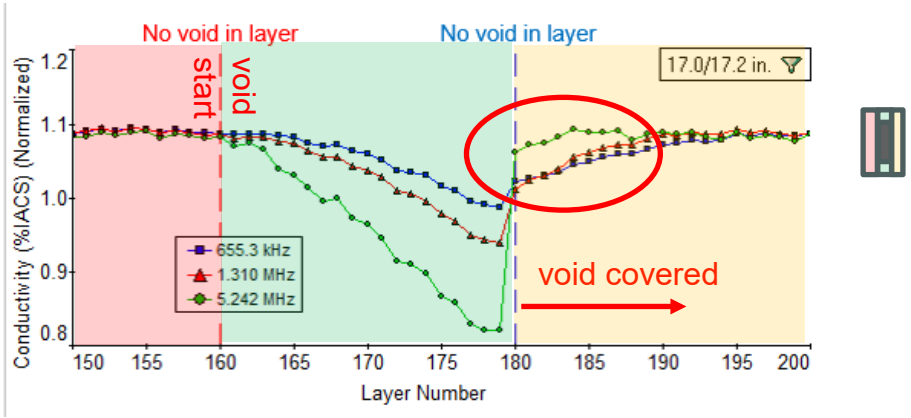
GE M2 Series 5

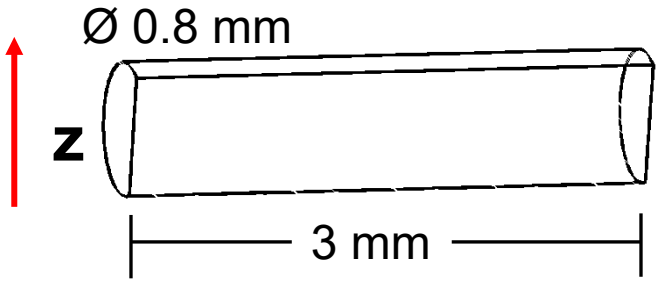


UDRI DART 2





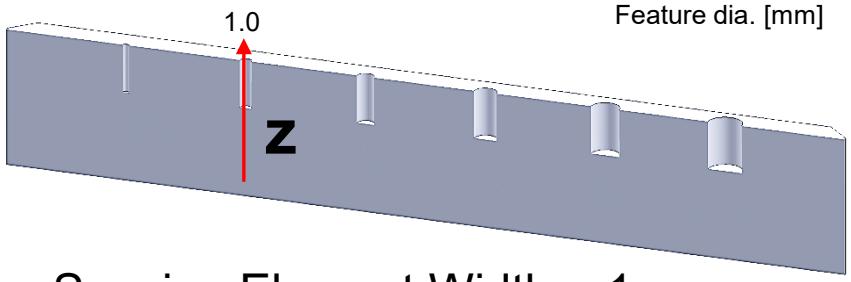




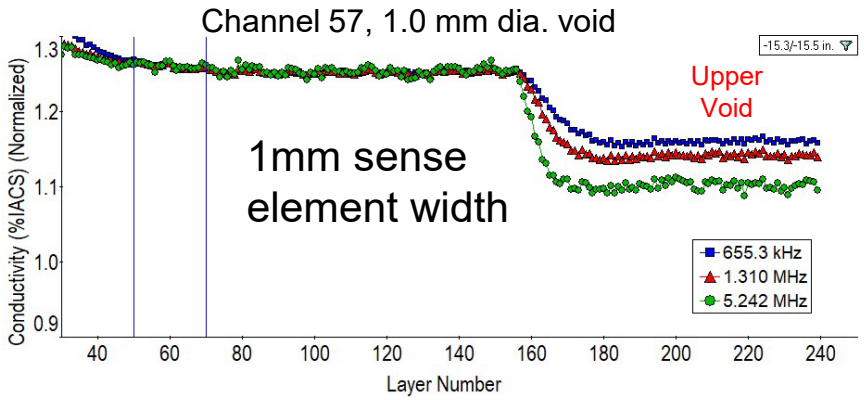
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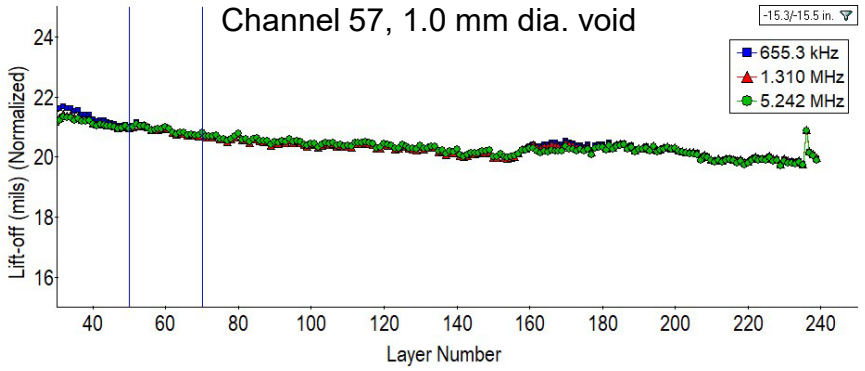
Sensing Element Size Comparison
GE M2 Series 5 (1mm) vs. UDRI DART 2 Data (1.5mm)

Build 1: GE M2 Series 5

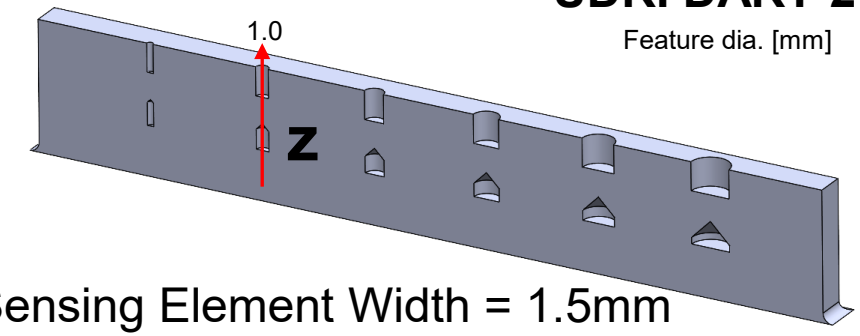


Sensing Element Width = 1mm

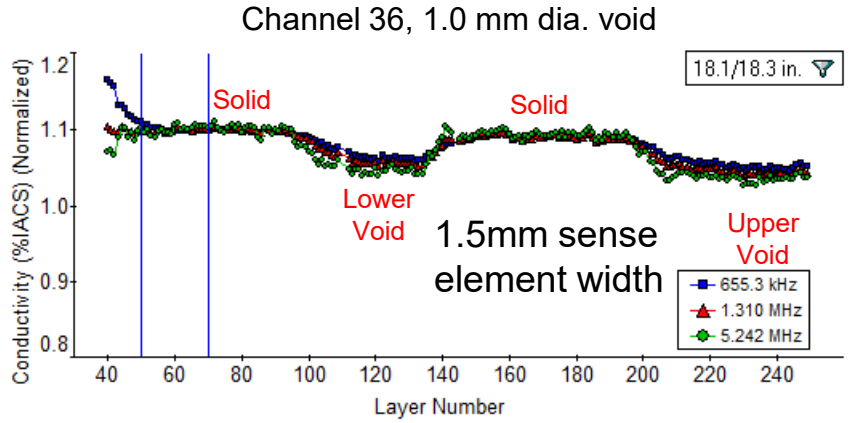


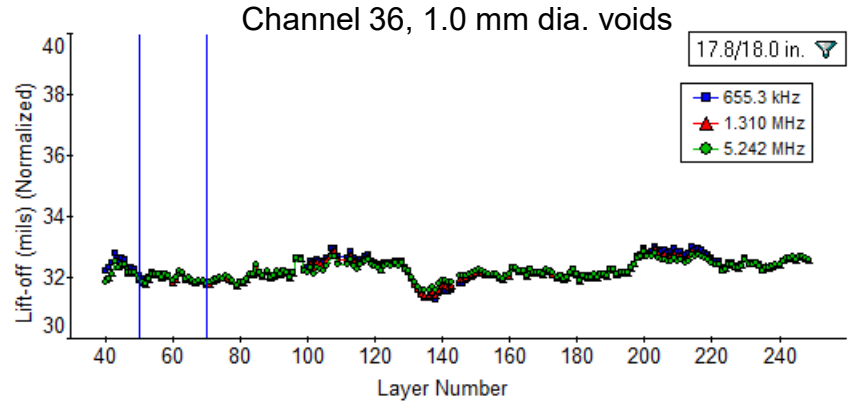


UDRI DART 2



Sensing Element Width = 1.5mm

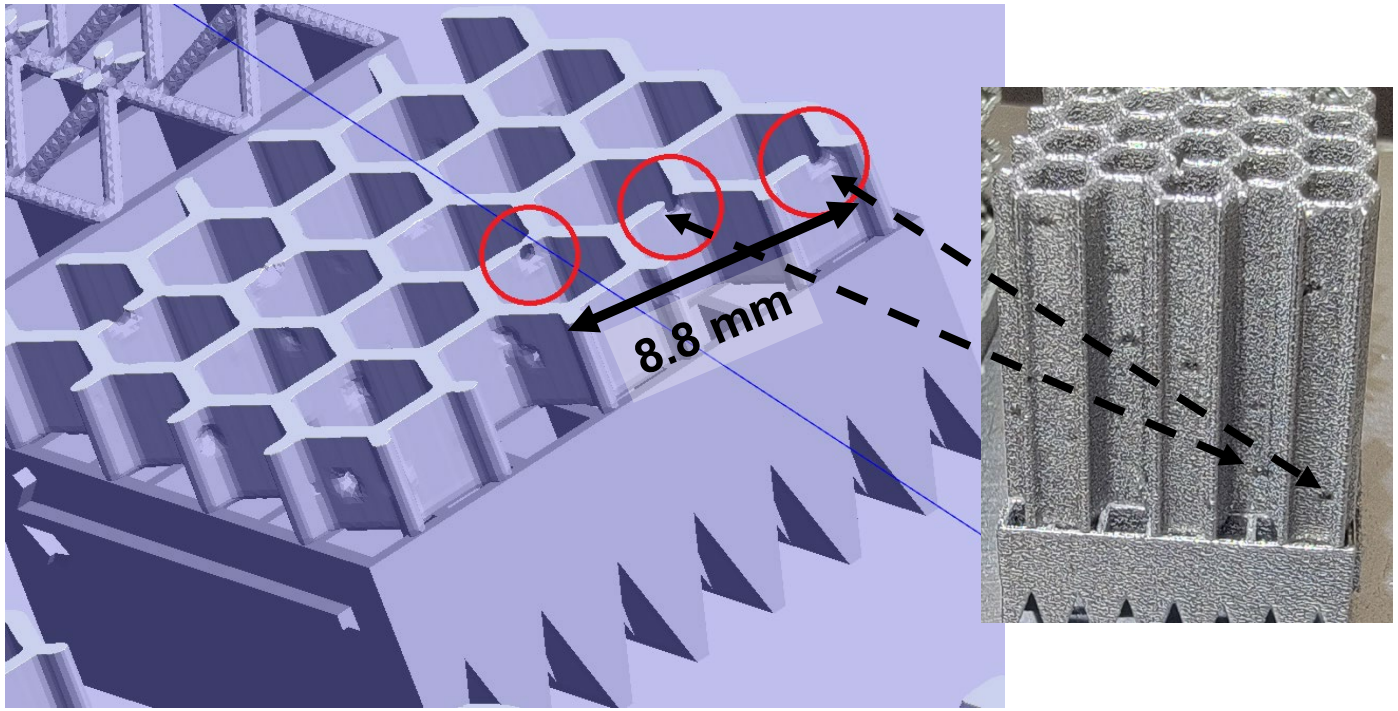


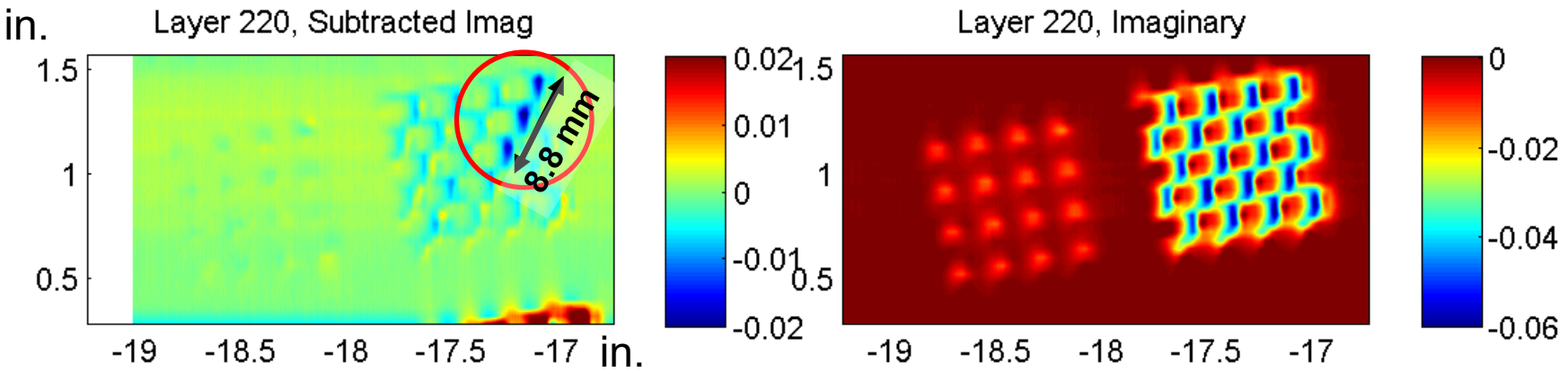


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Highly Repeatable Raw Data (Simple Good-Bad Image Subtraction)

- 1.3 MHz Image Subtraction
- Wall thickness: ~0.6 mm
- Three thru-wall Defects:
  0.35 mm, 0.5 mm, 0.55 mm



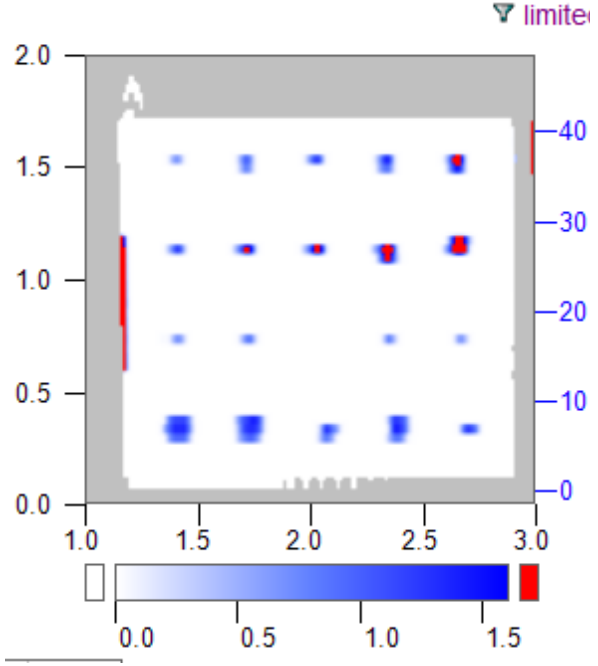


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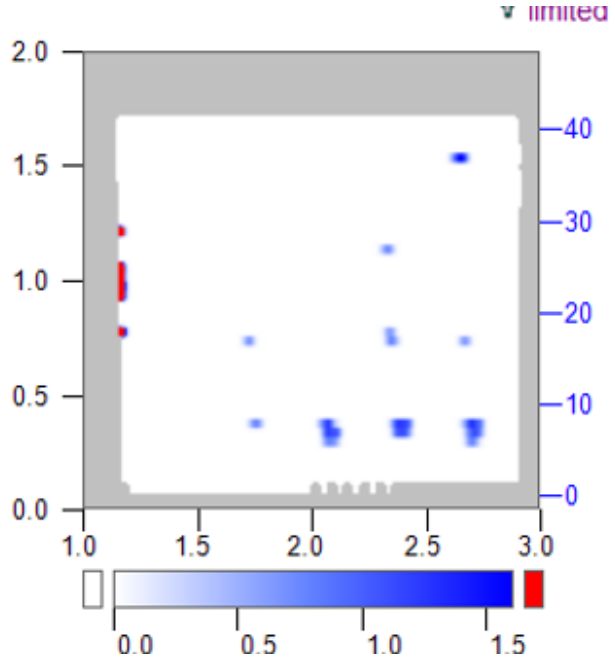
CCAM LPBF Sample Post-Fabrication Filtered Scan Data

- CCAM specimen
- Series of subsurface flaws
- Shape and orientation varied between rows
- Cover layer thickness varied along the row (60 um layer increments)
- Data processed with shape filtering
- Observations
  - All defects except one detected in filtered lower frequency responses

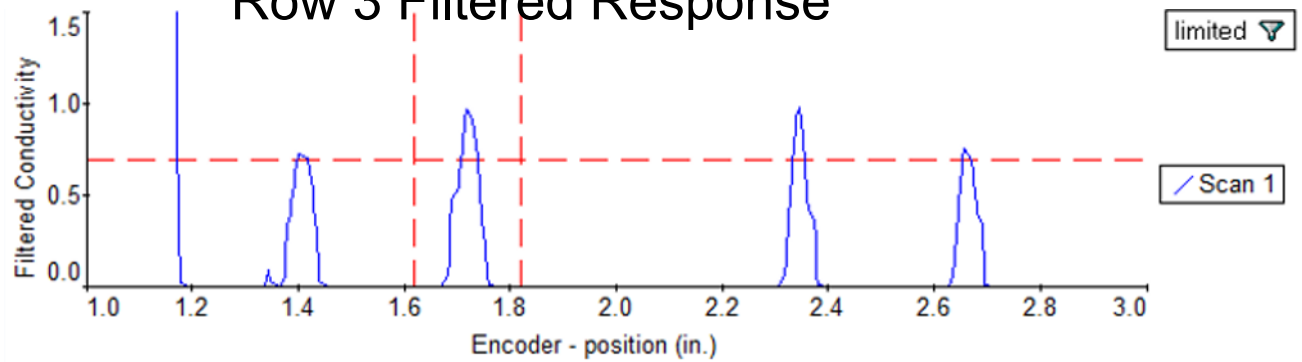
Lower Frequency)



Higher Frequency



Row 3 Filtered Response



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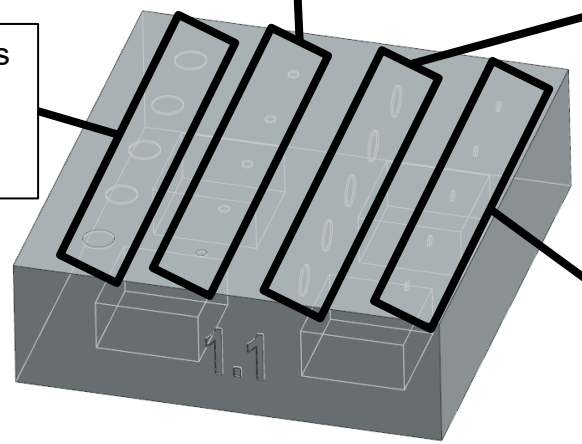
CCAM LPBF Sample Post-Fabrication Conductivity Scan Data

- CCAM subsurface flaws specimen
  - shape and orientation varied between rows and top layer thickness varied along the row (60 um layer increments)
  - Data processed here with standard half-space grids to convert raw data into effective conductivity and lift-off
- Observations
  - Lower frequencies more sensitive to the presence of subsurface flaws
  - Highest frequency sensitive to the larger and shallower flaws

- 1mm Ø Horizontal disks
- Voids 3 layers thick
- 1 to 5 layers below the part surface

- 3mm Ø Vertical disks
- Voids 3 layers thick
- 1 to 5 layers below the part surface

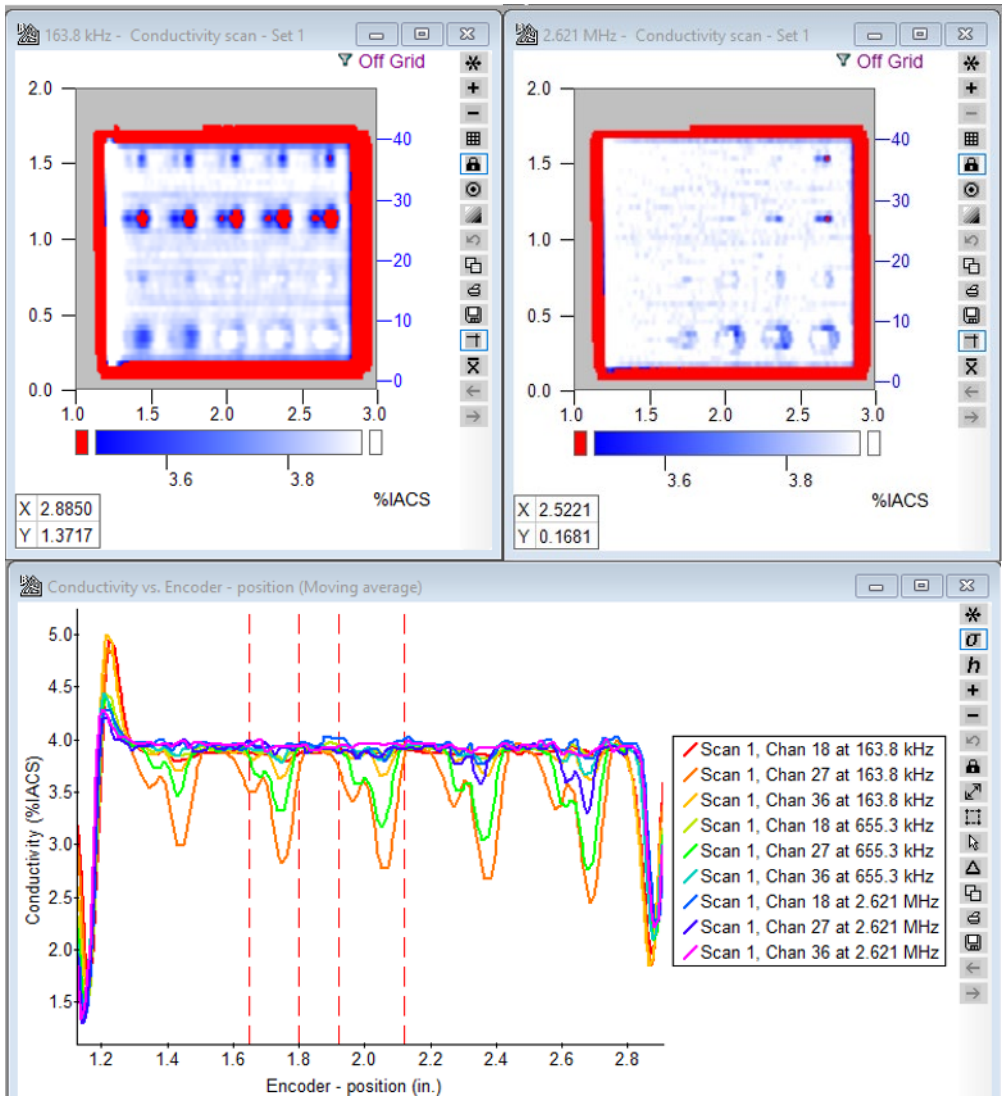
- 3mm Ø Horizontal disks
- Voids 3 layers thick
- 1 to 5 layers below the part surface



- 1mm Ø Vertical disks
- Voids 3 layers thick
- 1 to 5 layers below the part surface

Conductivity (163 kHz)

Conductivity (2.62 MHz)



Red dashed vertical lines indicate approximate extent of defects 2 and 3 from the left.

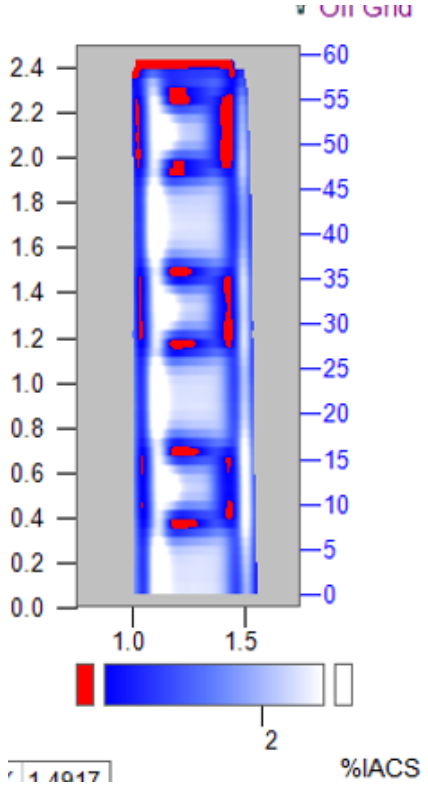
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Nested Block Specimen Scan Data

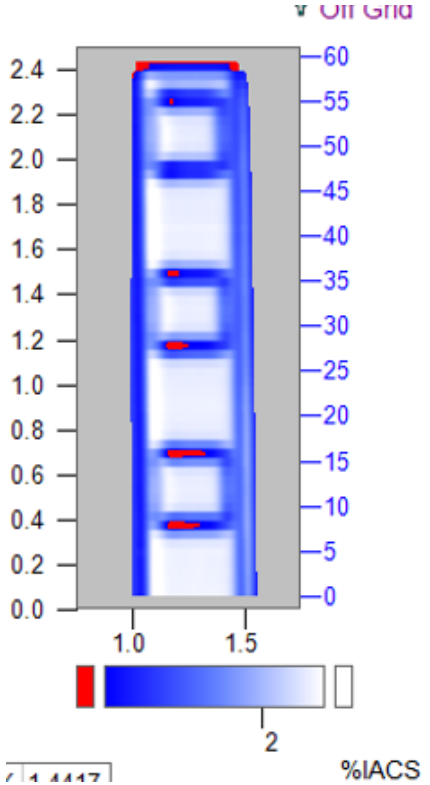
- CCAM specimen with several nested blocks of same material as base
- Data processed here with standard half-space grids to convert raw data into effective conductivity and lift-off
- Observations
  - Local conductivity decrease and lift-off increase at interfaces between insert and base material
  - Edge effects in scan direction can mask property changes from interfaces
- Future work is focused on improved filtering (AI/ML)



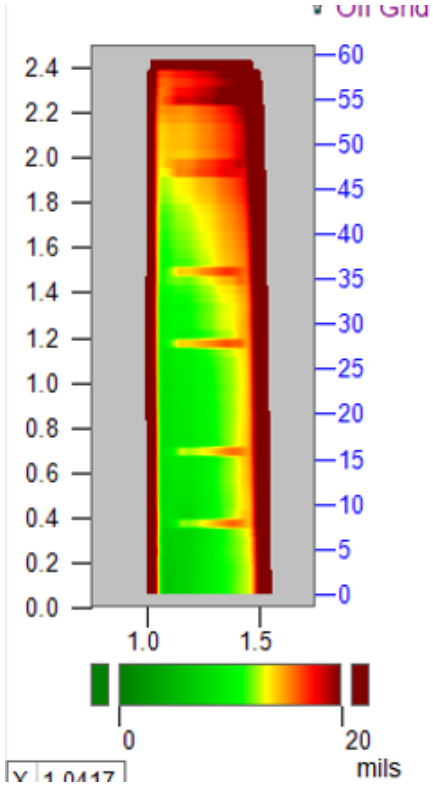
Conductivity (163 kHz)



Conductivity (2.62 MHz)



Lift-off (655 kHz)

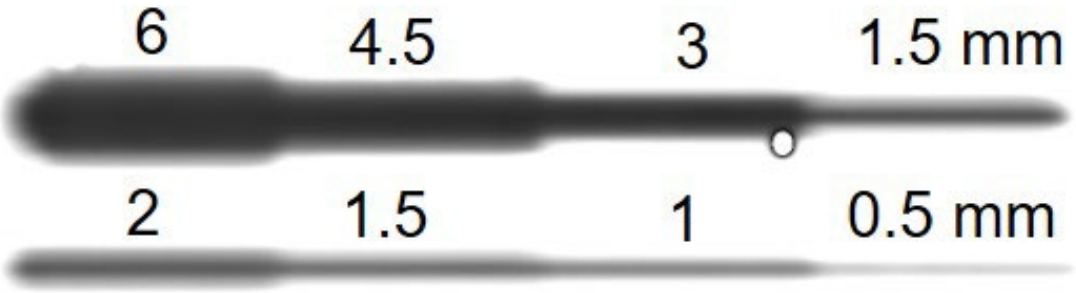


AM block with 3 nested cubes with the same processing parameters: manufactured in a single AM process

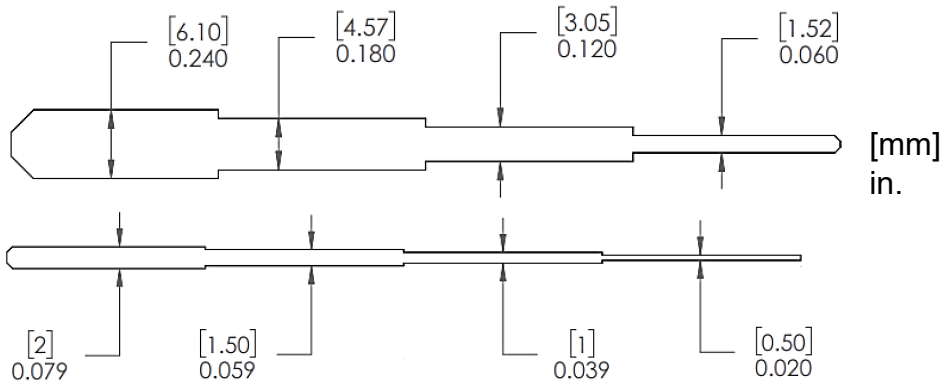
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Sub-Pixel Geometric Imaging

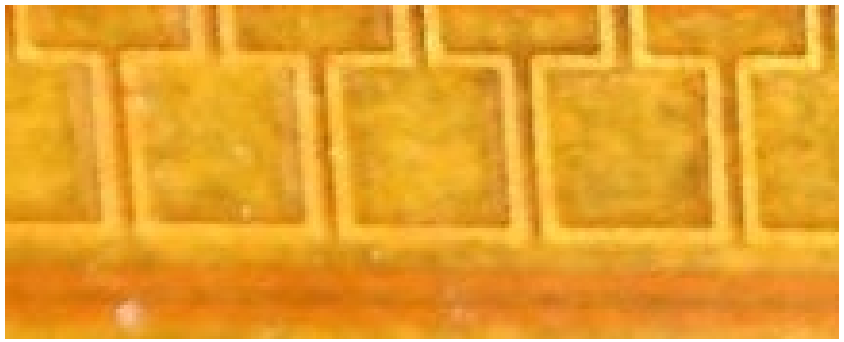
(likely requires fusion with optical or IR imaging)



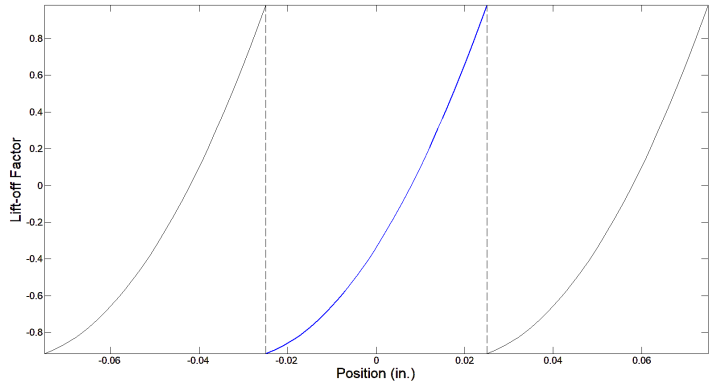
Wall Thickness Step Wedges



No Image Sharpening Applied







Analog Sub-Pixel Response will Enable Edge Sharpening

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DED & AFSD MWM-Array Technology Advantages

1. Conductivity and Geometric Bead Imaging (with Air Calibration)

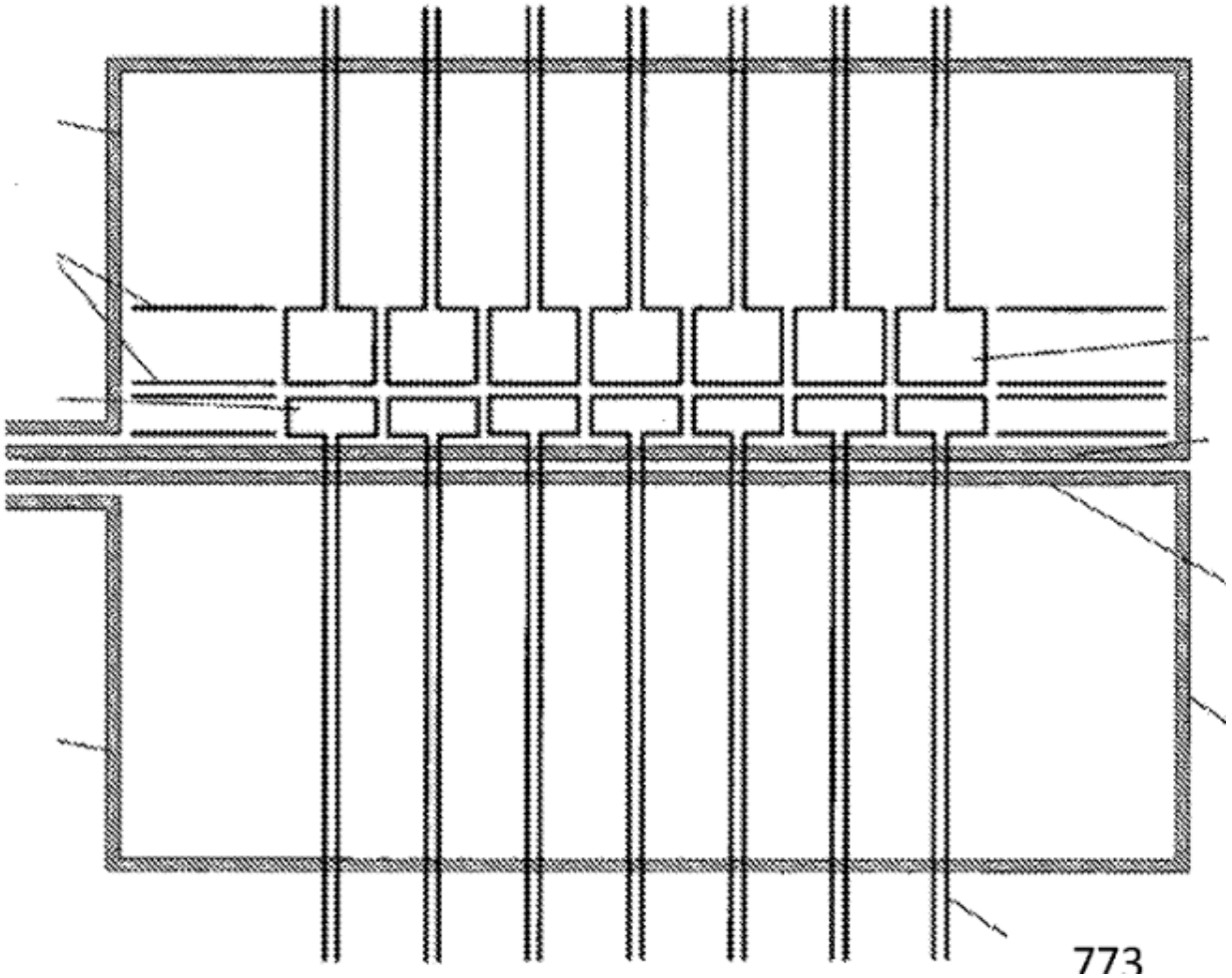
2. Conductivity Imaging for Prior and Neighboring Bead Including Fusion Zone (Using Rapid Physics Solver)

3. Surface and Subsurface Defect Detection (only most recent and prior layer using AI/ML training)

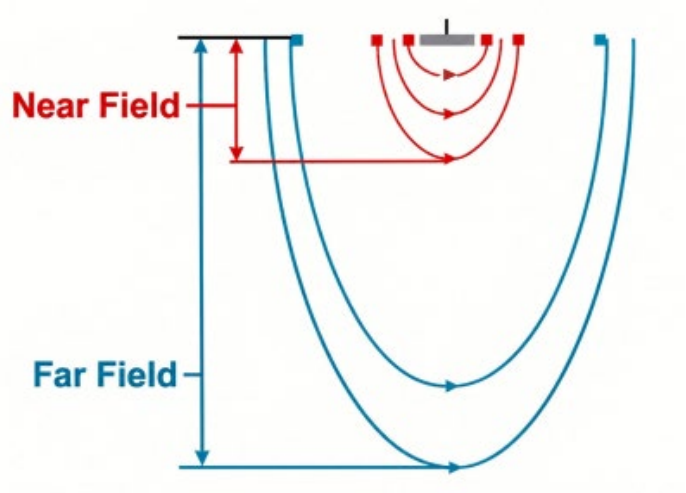
4. Real-time Control/Rapid Data Processing (including active liftoff control)

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Segmented Field MWM-Array Sensing and Advantages



- 3 Frequencies Simultaneously on all sensing elements simultaneously
- Two sensing element rows with different penetration depth for fields



- Real-time liftoff control
- Rapid Physics Solver
- Response independent of sensor temperature
- Can correct for varied liftoff up (2-5mm range)
- Wide area coverage for current and neighboring beads

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Ongoing/Planned 2026/2027 DED and AFSD Integration & Testing

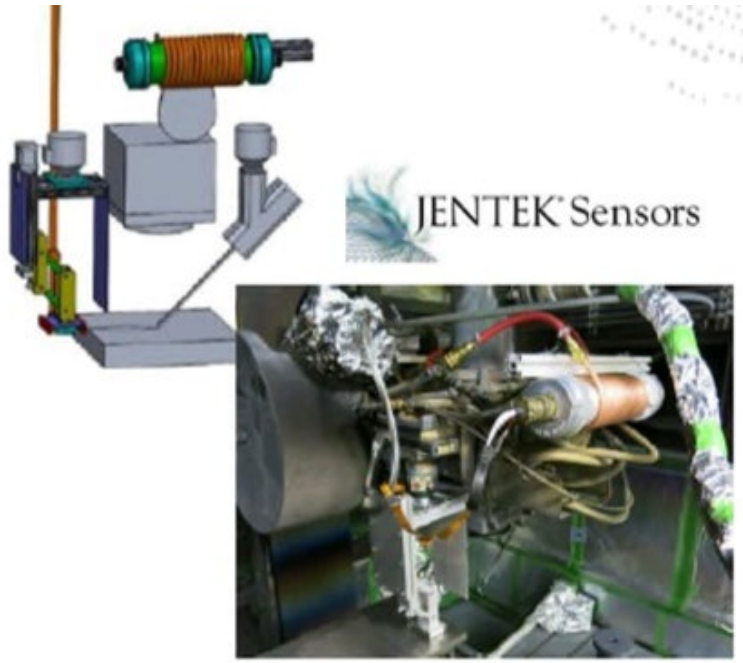
Integration and Testing Plans

- First MWM-Array DED Demo was over 5 years ago, for EB-DED
- Planned integrations for 2026 include two different Laser-Wire-DED commercial installations.
- Planned efforts for 2027 include Wire Arc Additive Manufacturing (WAAM) installations and testing

Current and pending capabilities

- MWM-Arrays commercially available can operate up to 250˚C with liftoff up to 2mm
- New MWM-Arrays for 250˚C for up to 3mm depth of penetration and 3mm liftoff soon.
- Next generation MWM-Arrays for up to 450˚C are under development for multiple uses.

First DED integrated demonstration of MWM-Arrays was over 5 years ago, for EB-DED



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JENTEK Additive Manufacturing Patents

Issued Patents

- 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

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AFSD (Additive Friction Stir Weld) work

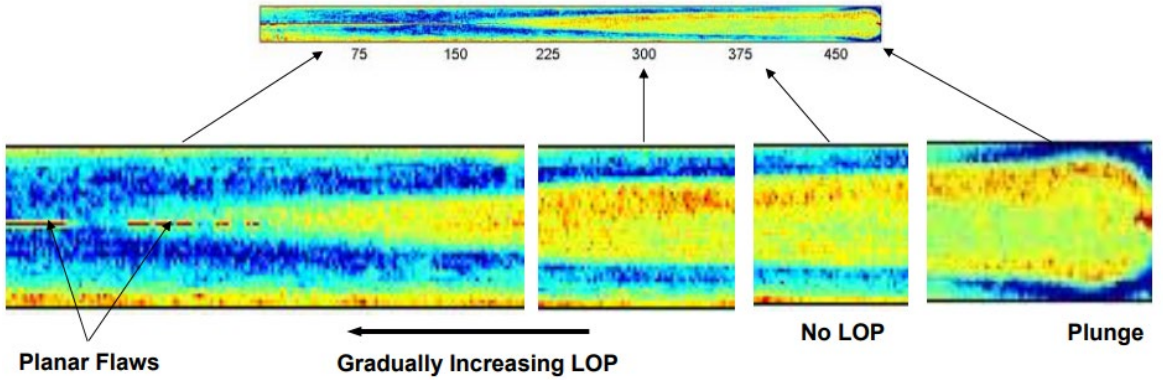
Prior work on FSWs

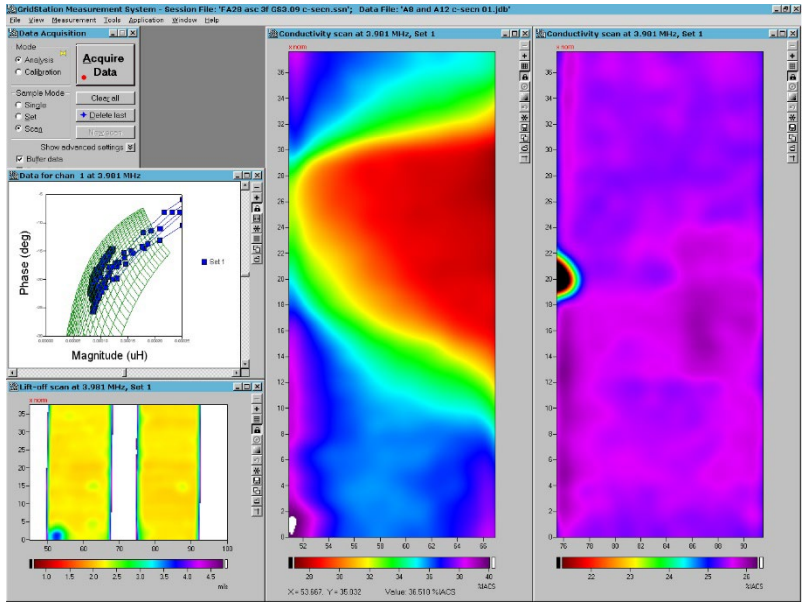
- JENTEK began work on Friction Stir Weld NDT with LM (Bill Arbagast) and NASA in the late 1990s.
- JENTEK delivered the first FSW inspection systems to LM and NASA around 2002.
- JENTEK has delivered multiple systems for FSW NDT over the last decade.

Current and pending AFSD work

- MWM-Arrays commercially available can operate up to 250˚C with liftoff up to 2mm
- Ongoing work is focused on integration and testing for AFSD.
- Pending work for 2027 expected to expand integration and testing efforts.

Prior FSW results





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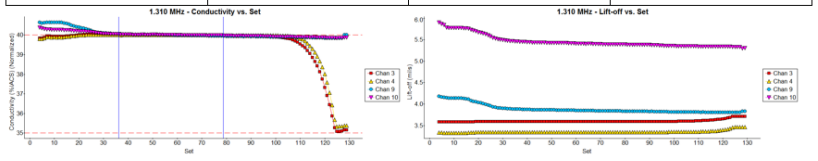
Hole Crack Initiation Studies and Real Crack Specimen Fabrication

Material	Thickness (in)	Hole Diameter (in)
6061-T6	0.125	¼ (0.250)

Note: Conductivity measurements are **NOT** consistent with 6061-T6

Maximum Load (lbs)	Minimum Load (lbs)	Frequency (Typical)	Max. # Cycles
3000	300	25Hz	19,773

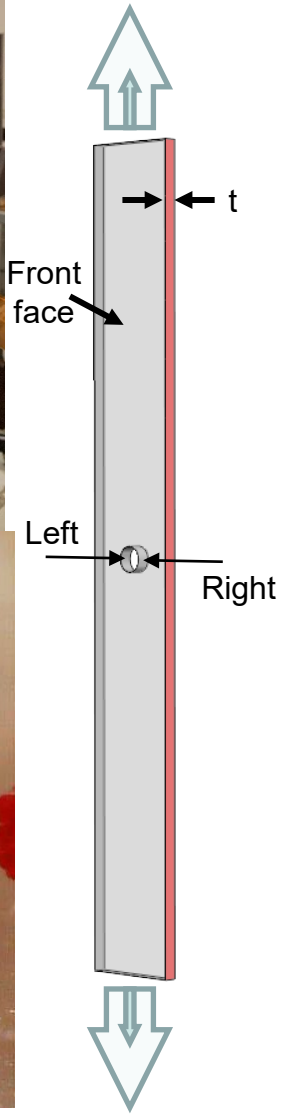
Left		Right	
Length in Hole (in)	Length on Surface (in)	Length in Hole (in)	Length on Surface (in)
0.000	0.000	0.044	0.018



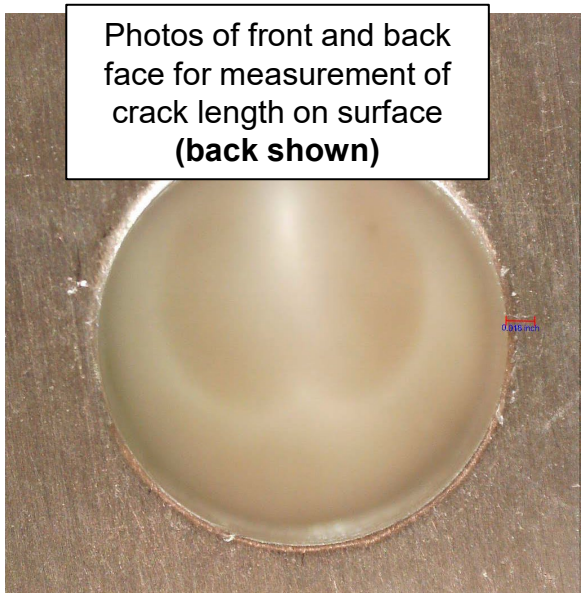
Sample **1**



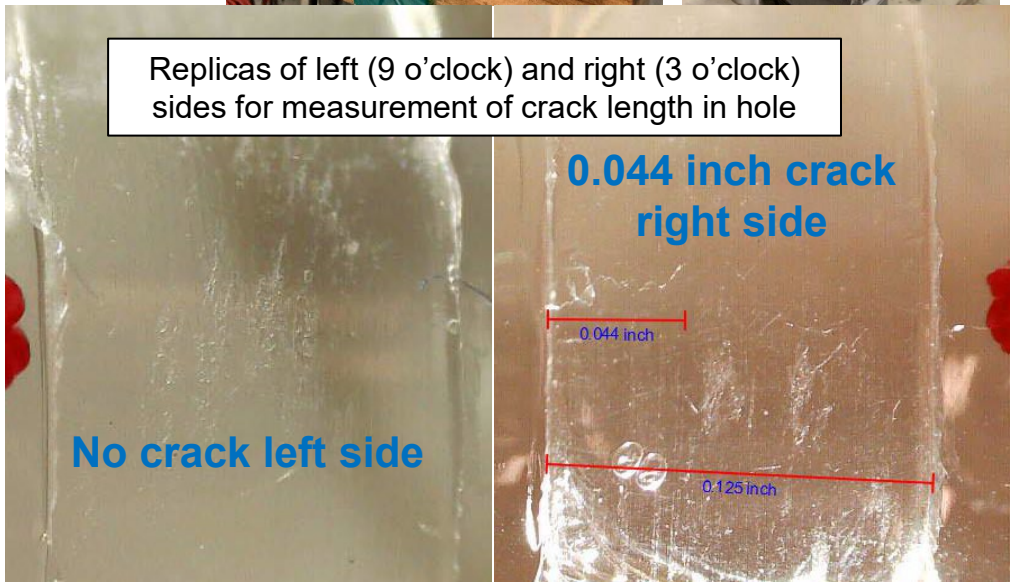




Photos of front and back face for measurement of crack length on surface **(back shown)**

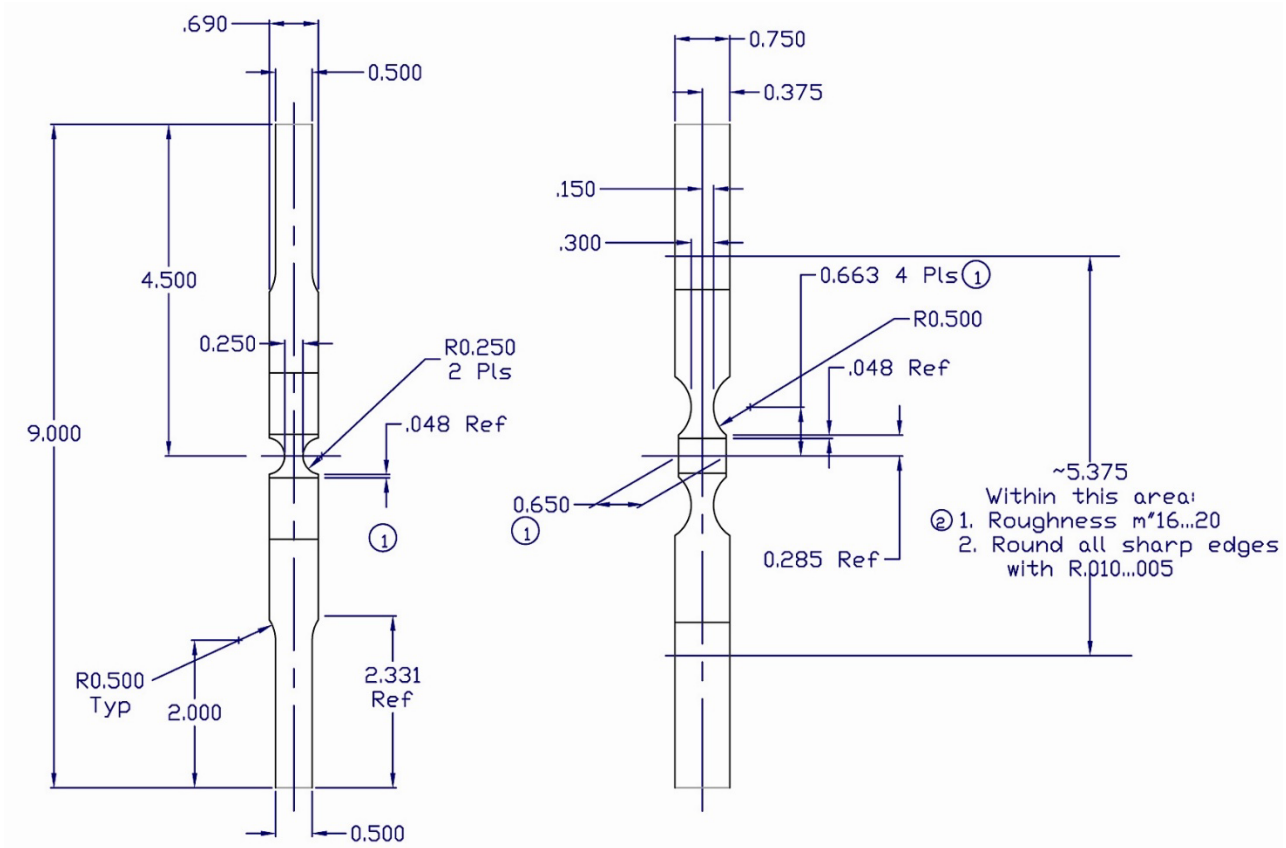


Replicas of left (9 o'clock) and right (3 o'clock) sides for measurement of crack length in hole

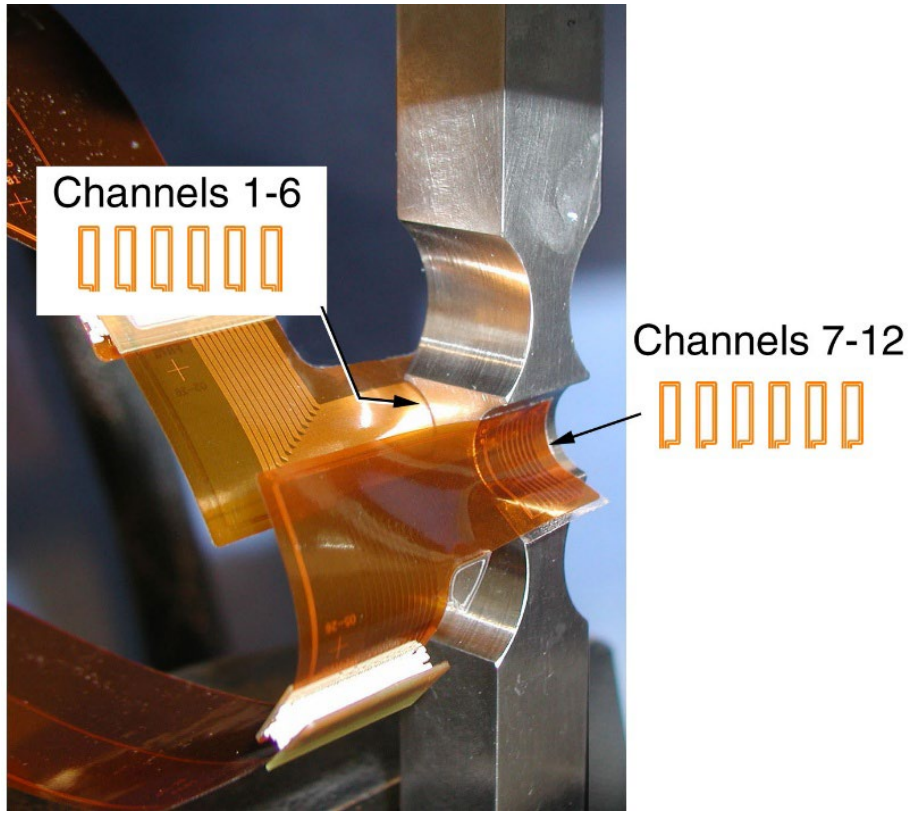


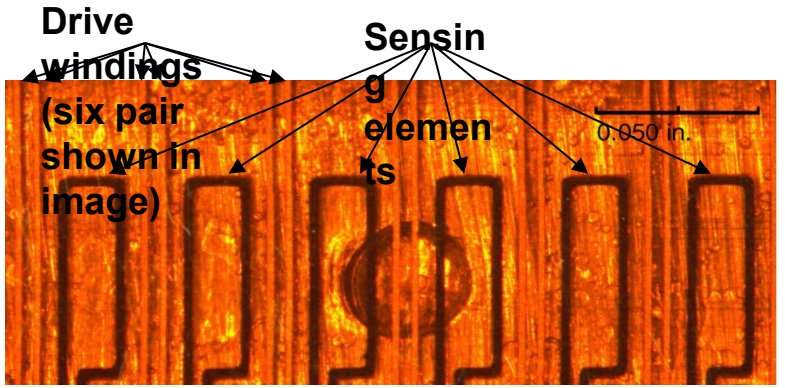
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Surface Fatigue Coupon Test Coupons for Crack Initiation Studies



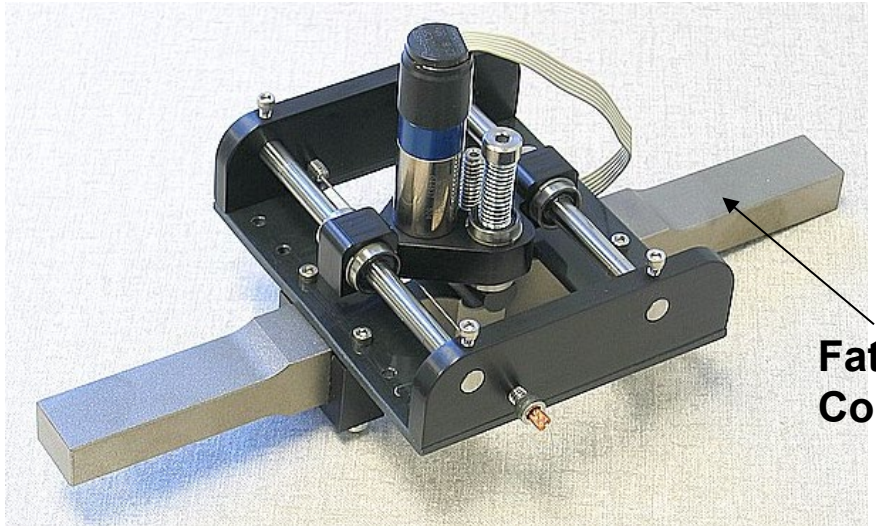


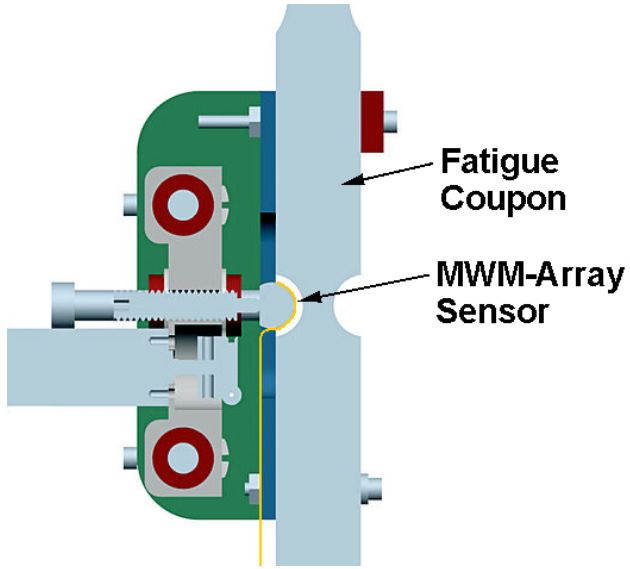




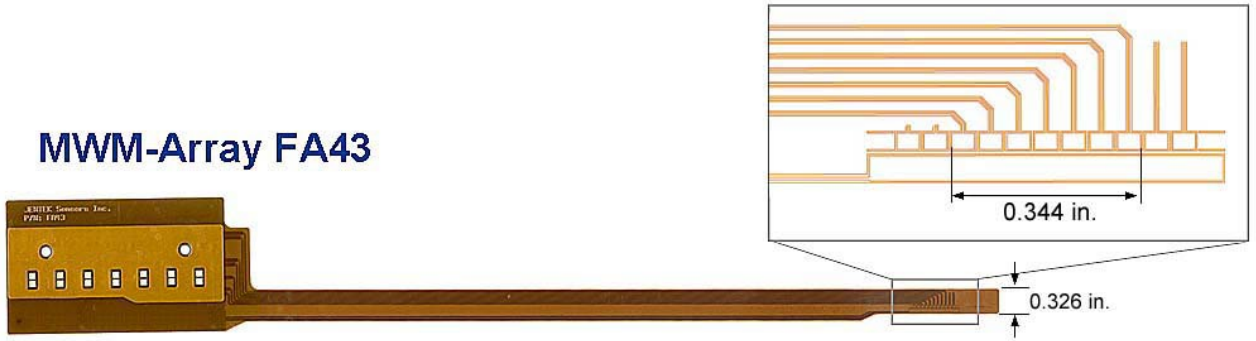
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Example MWM-Array Scanner for Fatigue Tests





MWM-Array FA43

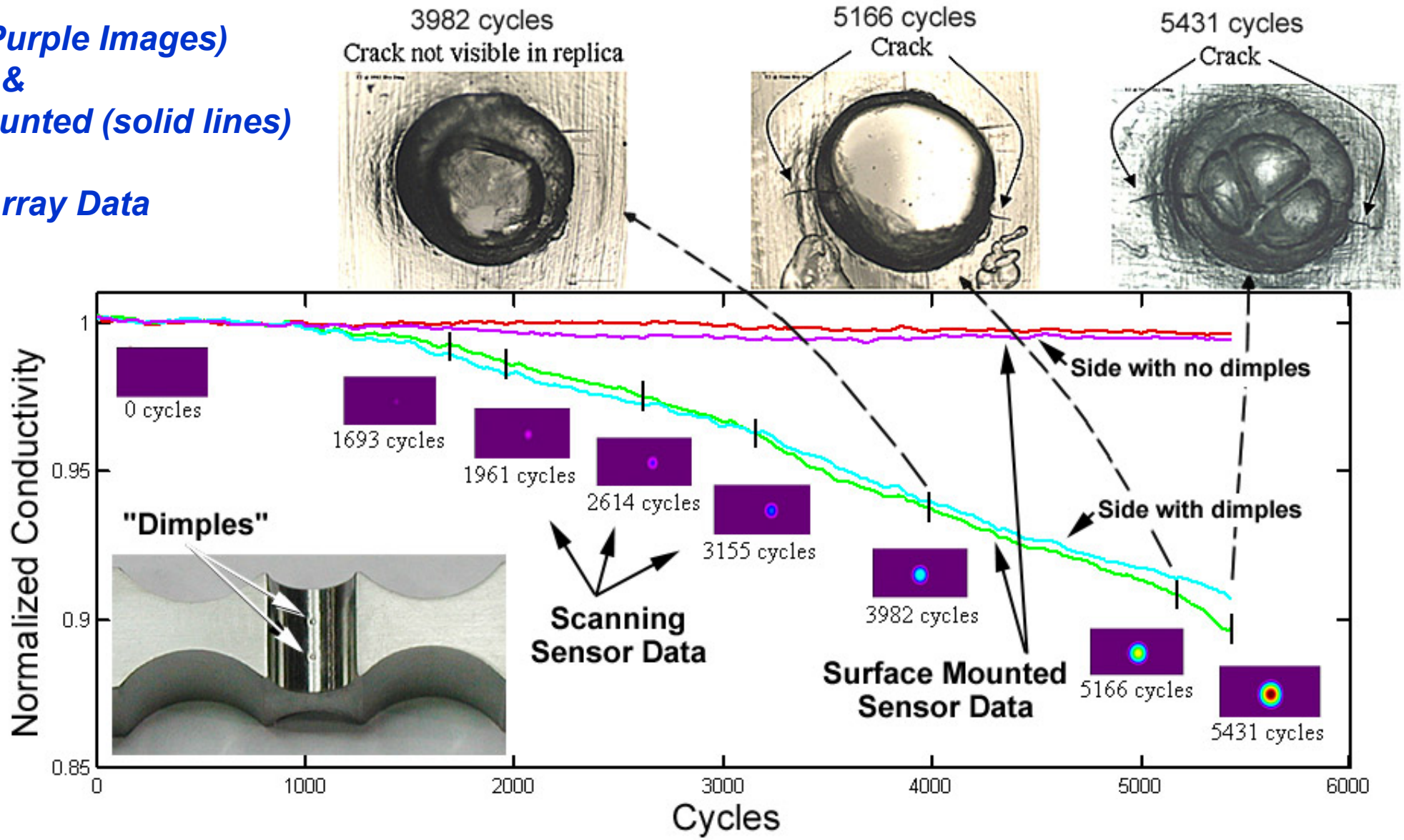


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MWM-Array (eddy current) Mapping and Tracking of Crack Initiation and Growth at "Dings" in Ti-6Al-4V

Scanning (Purple Images)
&
Permanently Mounted (solid lines)

MWM-Array Data



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Topics Addressed (Review)

- **JENTEK Technology and Products**
  - Impedance Instrumentation
    - Fully Parallel Multiple Frequency Instrumentation for DED and AFSD
    - Next Generation Multiplex and Miniaturized for LPBF
  - Data Analytics Software
    - Air Calibration and Rapid Physics Software (Multivariate Inverse Methods, MIMs)
    - AI/ML (Tools & Model Training Services for Defects and Quality) (Use NG investor briefing slides)
    - Automation Module for Integration (get from MW)
  - Engineering Services for Integration Support
- **Laser Powder Bed Fusion (LPBF) in-situ Eddy Current Array Layer-by-Layer Sensing & Inspection**
  - EOS M290 Data (with CCAM)
  - Dart 2 Data (with UDRI)
  - GE Concept M2 Data
  - CCAM Desktop NDT on LPBF Parts with JENTEK MWM-Array
- **Directed Energy Deposition (DED)**
  - Layer-by-Layer Near Real-Time Sensing & Inspection
  - Real-Time Following (and leading) for Qualification and Control
- **Additive Friction Stir Deposition (AFSD)**
  - Layer-by-Layer Near Real-Time Sensing & Inspection
  - Real-Time Following (and leading) for Qualification and Control
- **Fatigue Test Monitoring for AM Parts**

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