In-Process Eddy Current Array Sensing on a LPBF AM System

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Abstract

This presentation showcases a leap in capability for eddy current array imaging and defect detection in laser powder bed fusion (LPBF) machines. The JENTEK MWM-Array with GS9000 instrumentation offers eddy current sensing element sizes down to 0.75 mm (0.03 inches) with three simultaneous frequencies and simultaneous measurements for all sensing elements. Modules for up to 79 channels of sensing elements and one drive (a novel dual rectangle drive) enable not only defect detection, but also full volumetric imaging of effective electrical conductivity and geometry. This paper describes results of a recent demonstration at the University of Dayton Research Institute (UDRI) on its Dayton Additive Research Technology (DART) model 2 LPBF machine. Simple samples with embedded defects of various sizes and a complex part were built using nickel alloy 718. Data was acquired at nominal production speed for this machine, 101.6 mm/s (4 in/s), with excitation frequencies up to 10 MHz. The capability to detect relatively small defects (e.g., 0.4 mm diameter) was demonstrated with high signal-to-noise ratio using patented sensing and intelligent filtering methods. The next phase of development is focused on commercialization with machine agnostic installations for commercial machines, and performance validation to meet specific customer requirements, such as detection of defects of relevant size as a cost-effective alternative to computed tomography (CT) and providing reliable digital twin records for geometry and material properties.

Agenda

- Overview of installation and results
  - Installation details (machine, instrumentation, sensor, procedure)
  - Description of part build and defects
  - Example results
- Detailed eddy current array LPBF demo results
  - C-scan and B-scan images plots
  - Preferred direction (z-directed) filtering
  - 3D volumetric visualization from array data only
- Powder model
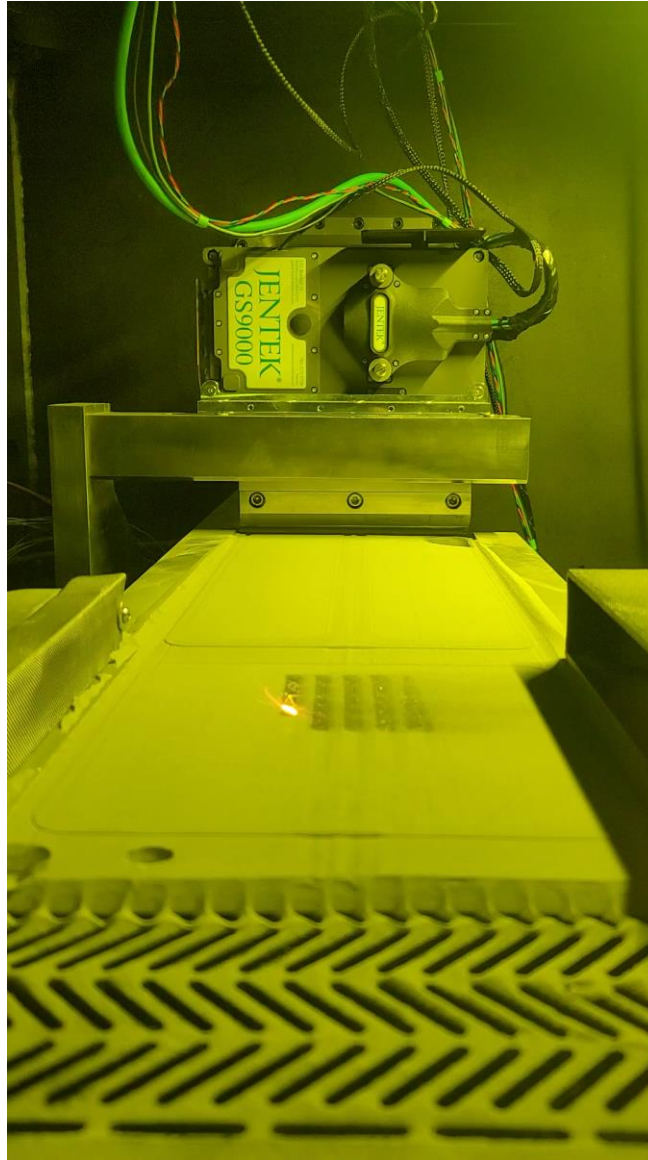- Future plans
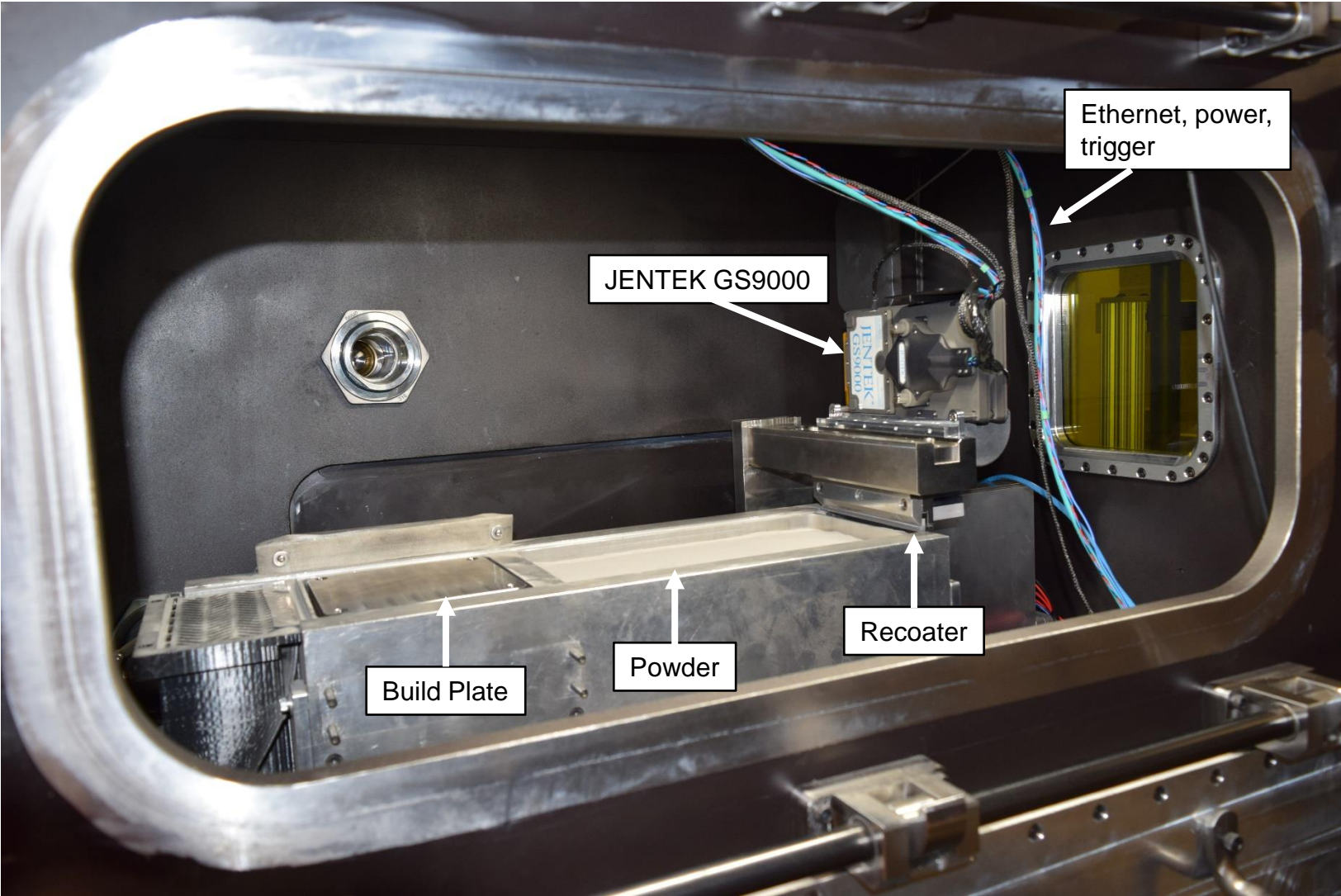
DART 2 System with GS9000 Installation

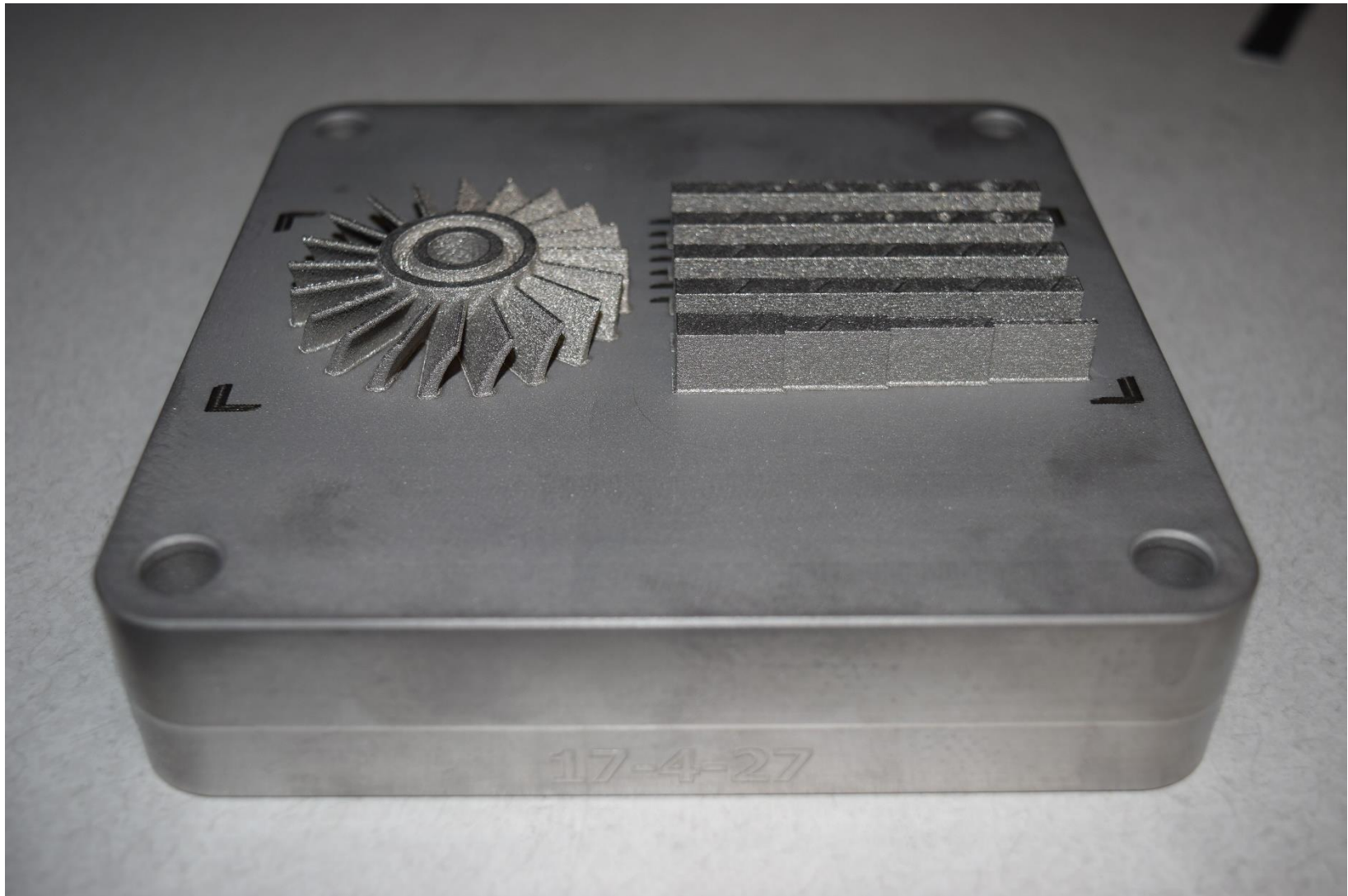# DART 2 System with GS9000 Installation

Recoater

Powder

JENTEK GS9000

39-Channel MWM-Array

Build Plate
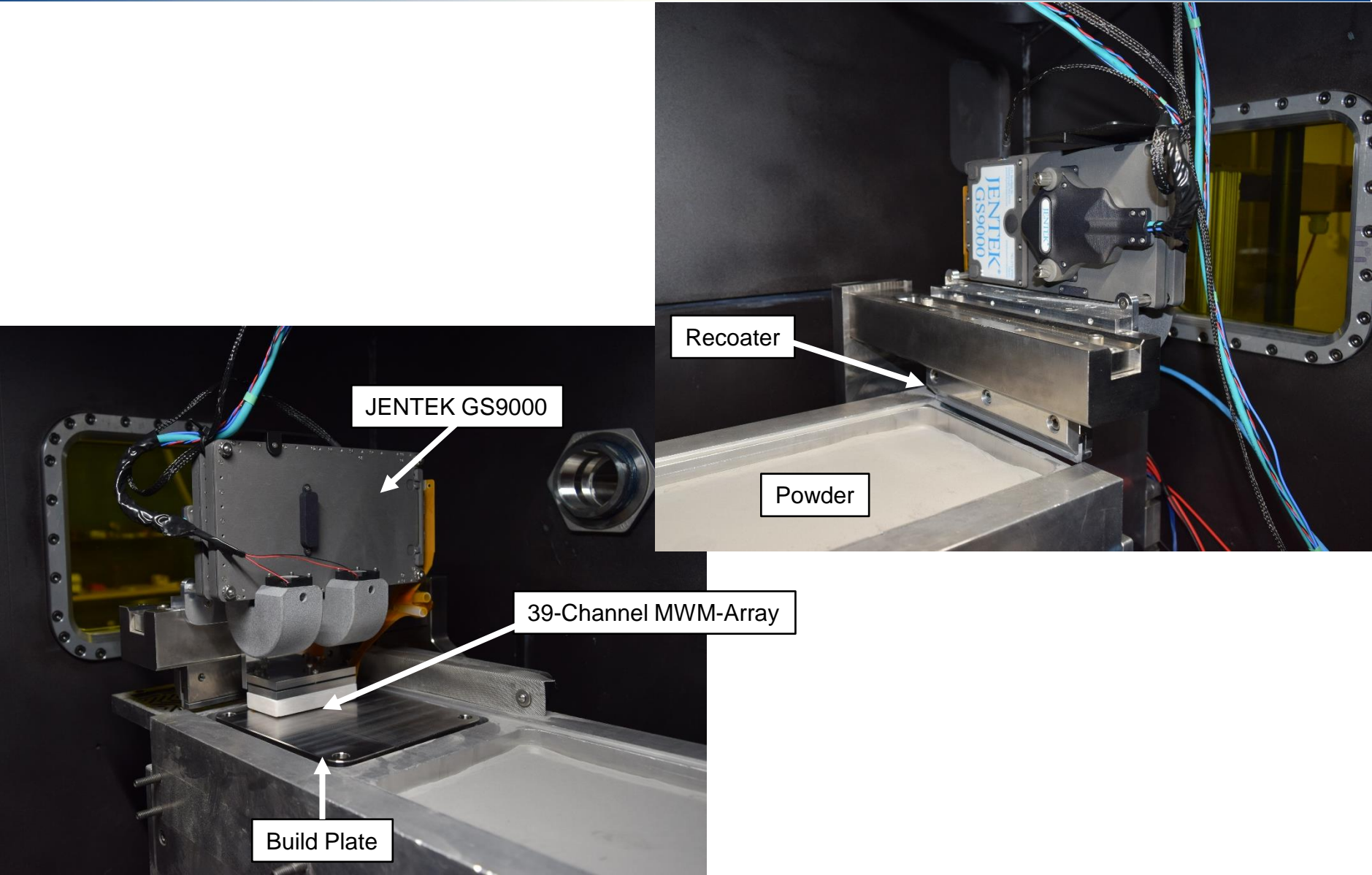
DART 2 System with GS9000 Installation (video)

JENTEK® Sensors, Inc.
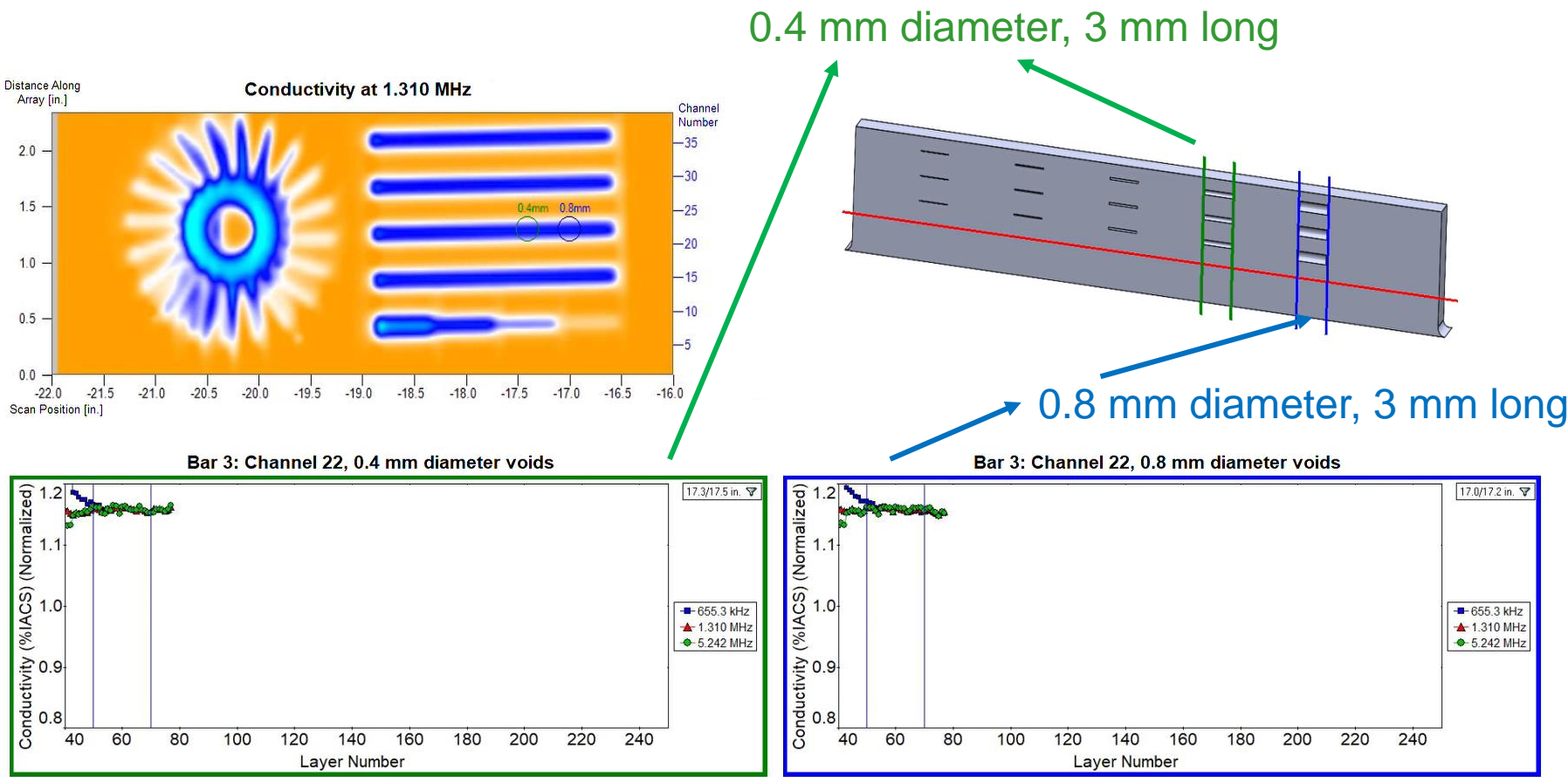
Photo of 249-layer Build (nickel alloy 718)

Conductivity C-scan and Z-directed Visualization

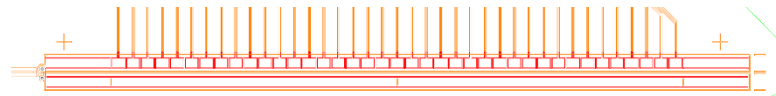**0.4 mm and 0.8 mm voids**

0.4 mm diameter, 3 mm long

0.8 mm diameter, 3 mm long

Note: %IACS = percent of International Annealed Copper Standard and 1%IACS = 0.58 MS/m

Build Configuration

- Inspection Details
    - 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 (1,280 meas / sec.)
    - Frequencies: 655 kHz, 1.31 MHz, 5.24 MHz (also demonstrated 10.5 MHz in other builds)

- Sensor array characteristics
    - MWM-Array: FA358
    - Sense element size: 1 x 1.5 mm [0.04 x 0.06 in.]
        - Can be as small as 0.75 x 0.75 mm [0.03 x 0.03 in.]
    - Scan width of MWM-Array: 59.4 mm [2.34 in.]
    - Number of channels: 39 (for this test but can be larger)

- 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.]

- 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: for 250 layers and 22 in. scan, 2.5 GB for raw and 5 GB including basic property estimates
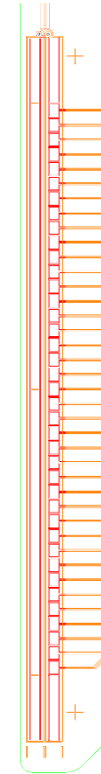   - Rough estimate is 45 MB per 100 layers per inspection inch for raw data for these typical settings
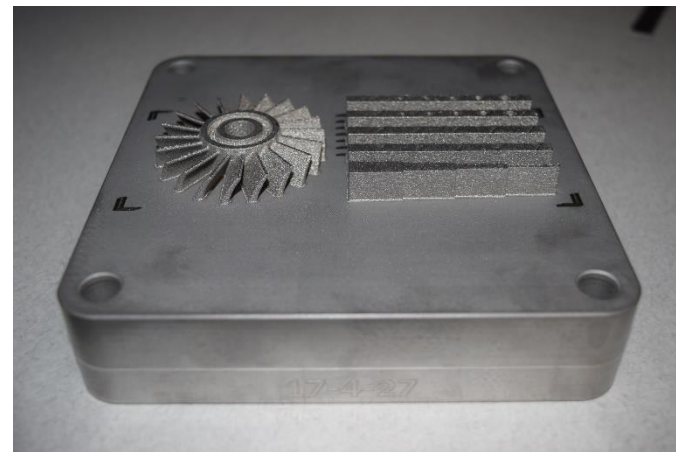
Build Nominal Geometry

Build Plate
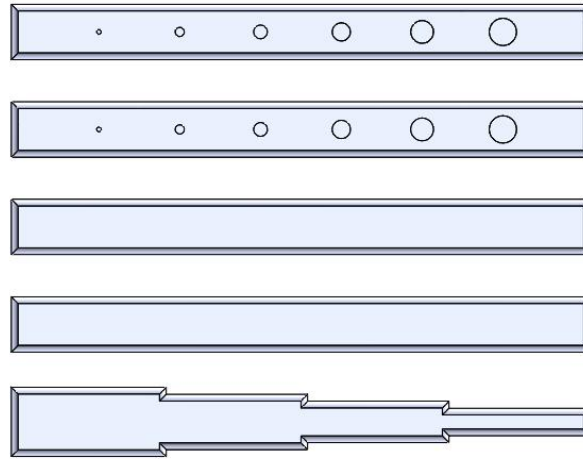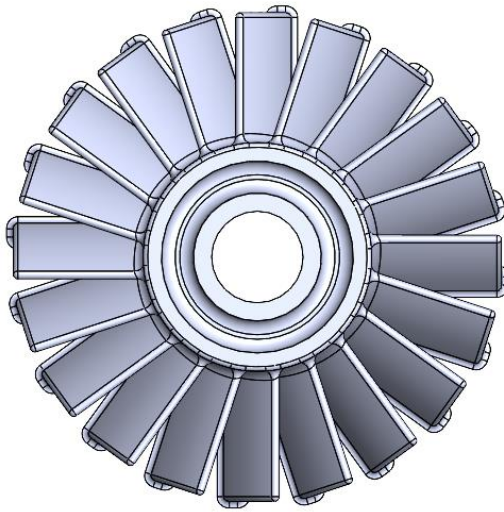
MWM-Array mounted
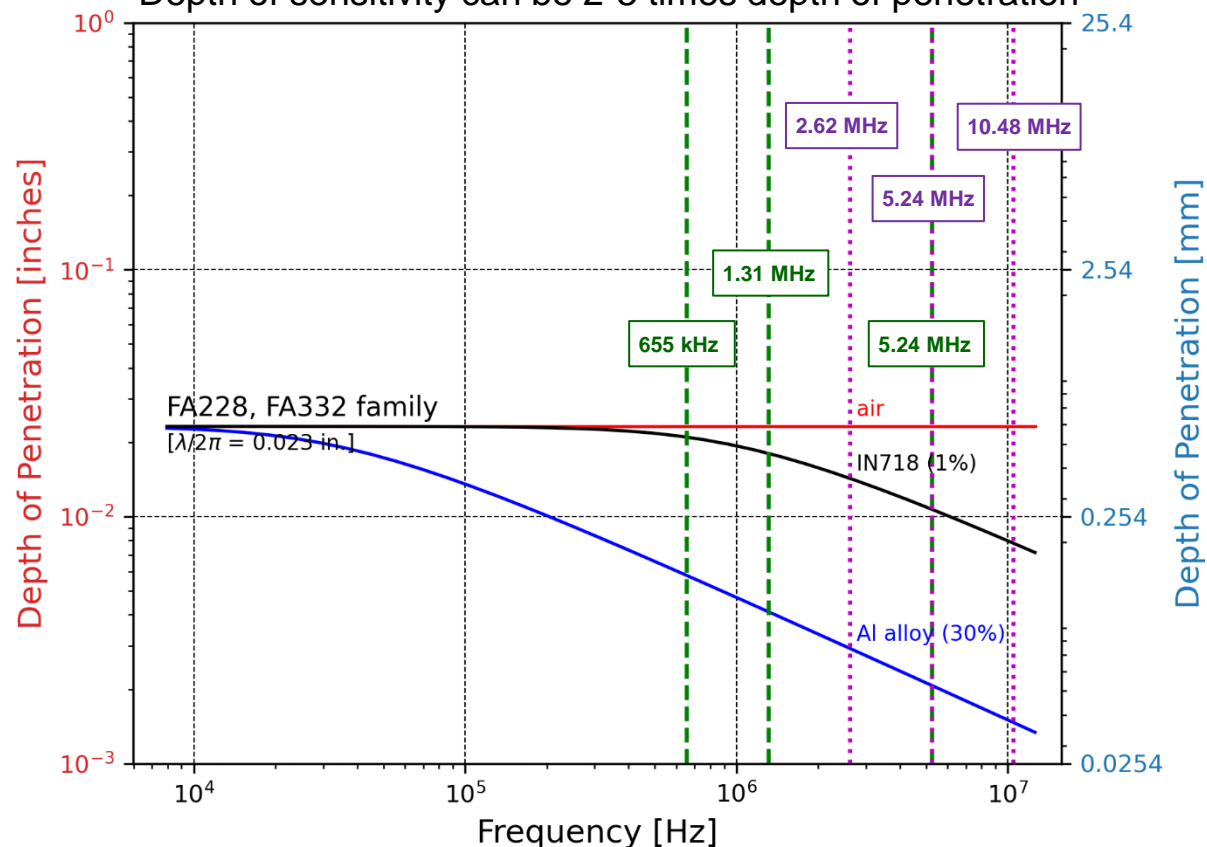to recoater

Channel 39

Base of Build Chamber

Channel 1

Scan direction

Depth of Penetration (two frequency sets)

- Magnetic field decay ~ exponentially with distance away from drive winding
- Decay rate in material determined by material properties and sensor geometry
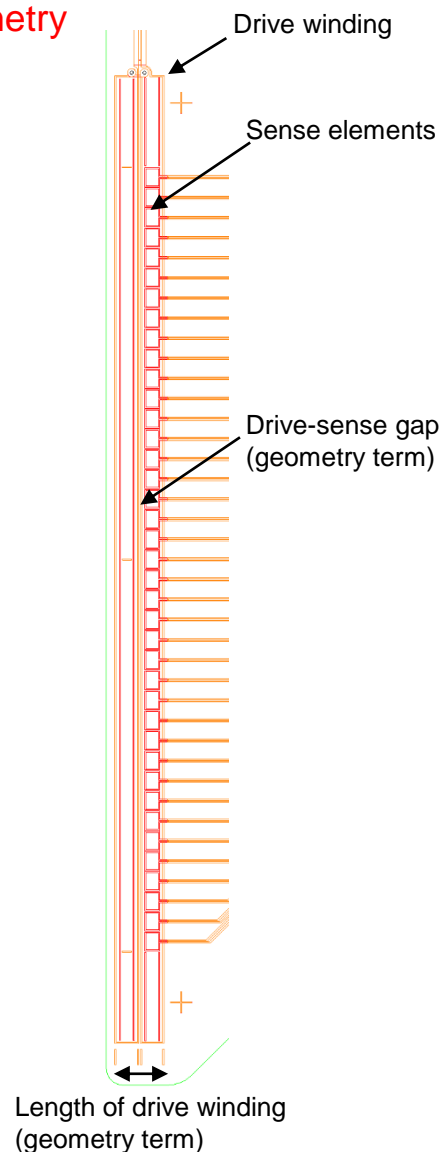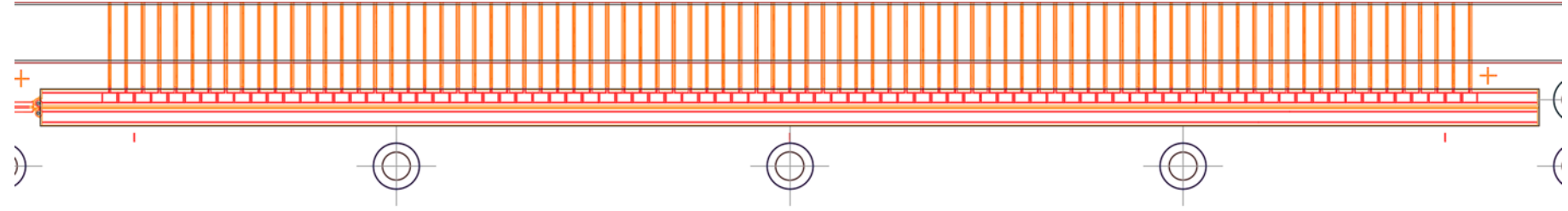- Depth of sensitivity can be 2-3 times depth of penetration

Example JENTEK Sense Element Size Options

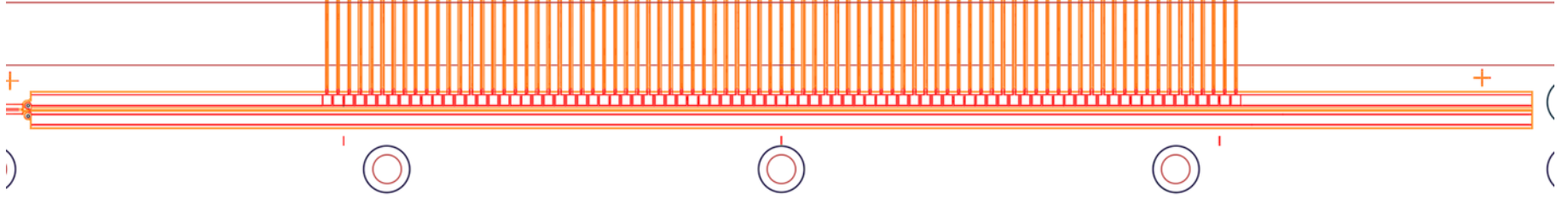FA332 (for comparison)
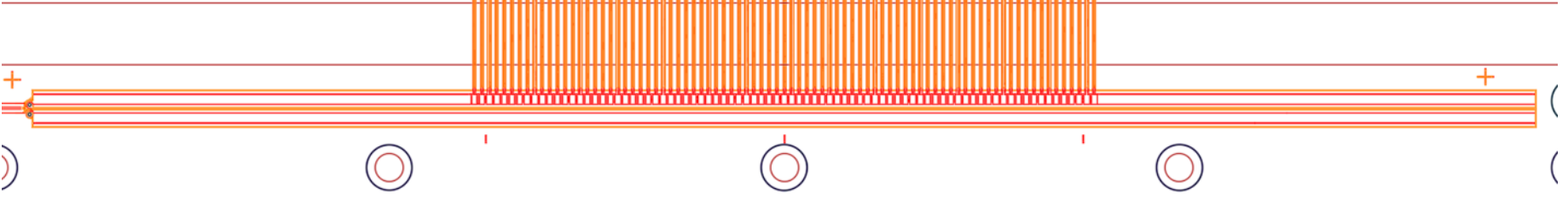1.65 mm sense element
130.0 mm scan width

FA364
1.10 mm sense element
86.9 mm scan width

FA366
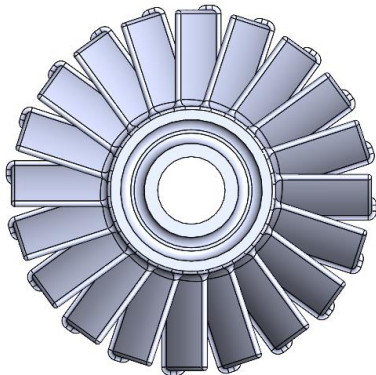0.75 mm sense element
59.25 mm scan width

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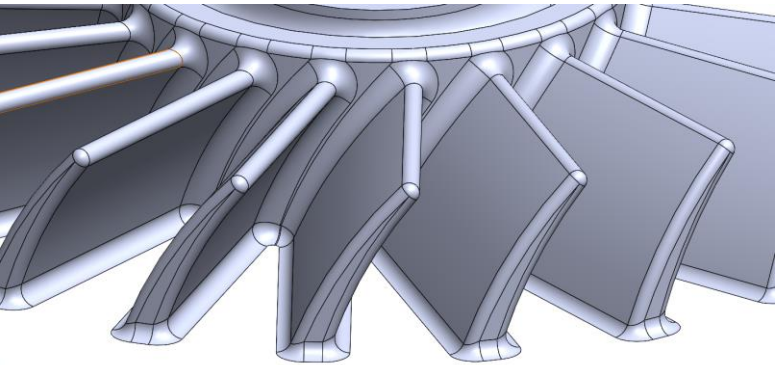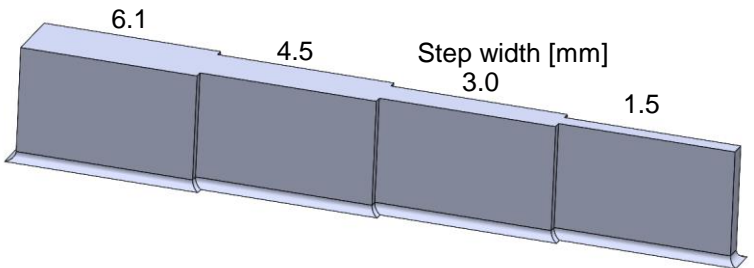# Build Geometry Model Details

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.]

Layer 227
Layer 112
Layer 80

0.5
1.0
1.5
2.0
2.5
3.0
Feature dia. [mm]

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.

Layer 227
Layer 112
Layer 80

0.04
0.08
0.16
0.40
0.80
Feature dia. [mm]

Layer 227
Layer 112
Layer 80

1.2
1.4
1.6
1.8
2.0

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

6.1
4.5
Step width [mm]
3.0
1.5

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

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Example 5.24 MHz, Impedance Data

Distance along Array [in.]

Real (In-Phase) Part

Channel Number

Imaginary (Out-of-phase) Part

Layer 80

Layer 112

Layer 227

Scan position [in.]

(uH)

(uH)
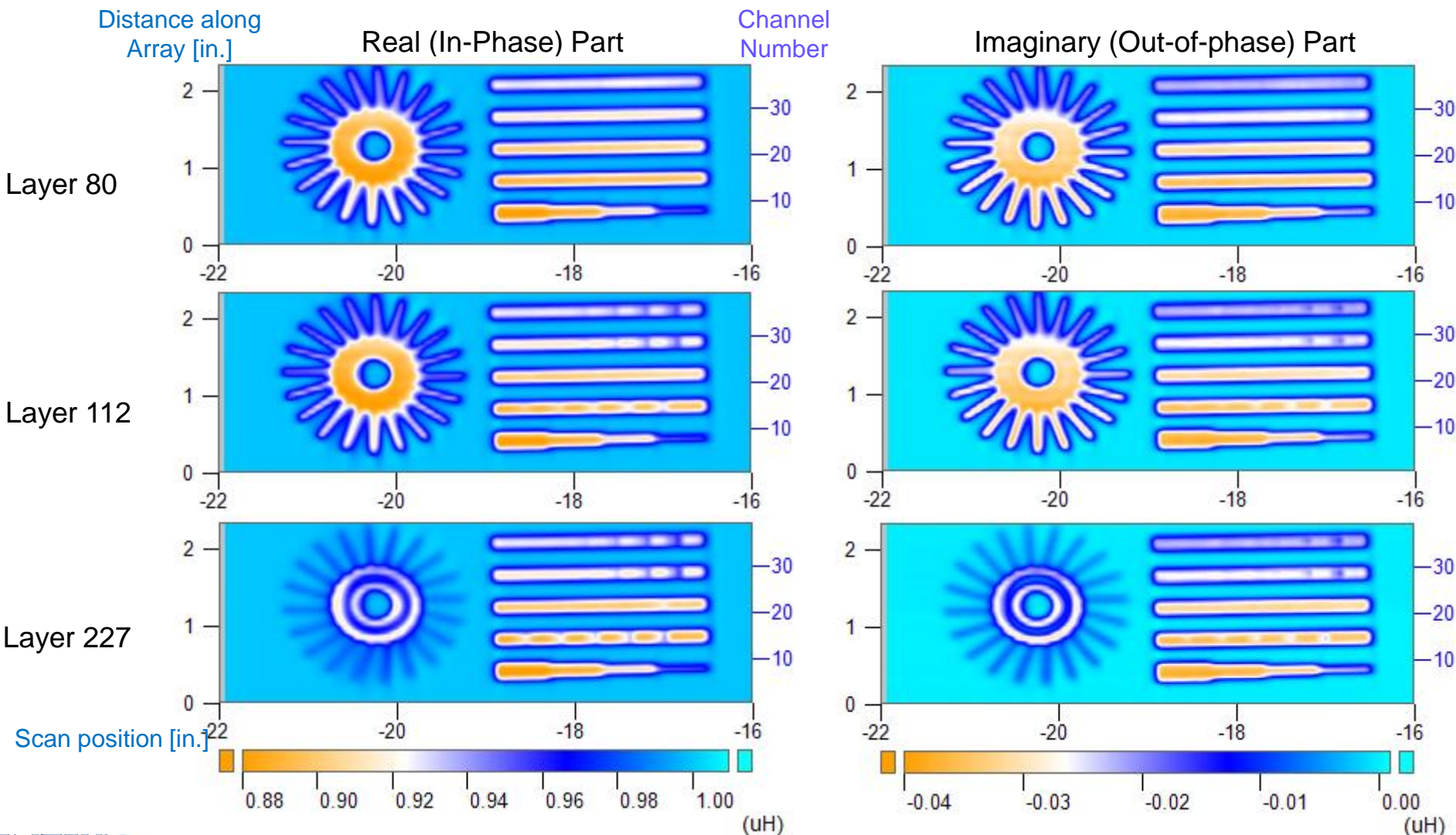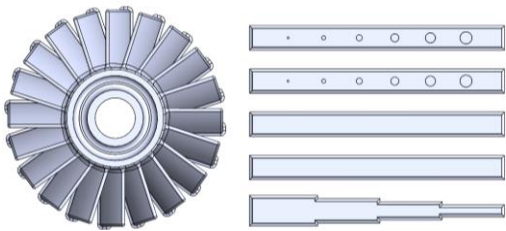
Example 5.24 MHz, Property Data

Distance along
Array [in.]
Effective Conductivity
Channel Number
Effective Lift-off

Layer 80

Layer 112

Layer 227

Scan position

%IACS

mils

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Example 1: B-Scan Plots

Scan direction

Bar 1

Feature dia. [mm]
0.5
1.0
1.5
2.0
2.5
3.0

Lower voids are 2.00 mm tall
Upper voids are 2.19 mm tall .

Layer 112
Layer 80

Bar 1: Channel 36

Bar 1: Channel 36

Layer 80

Layer 112
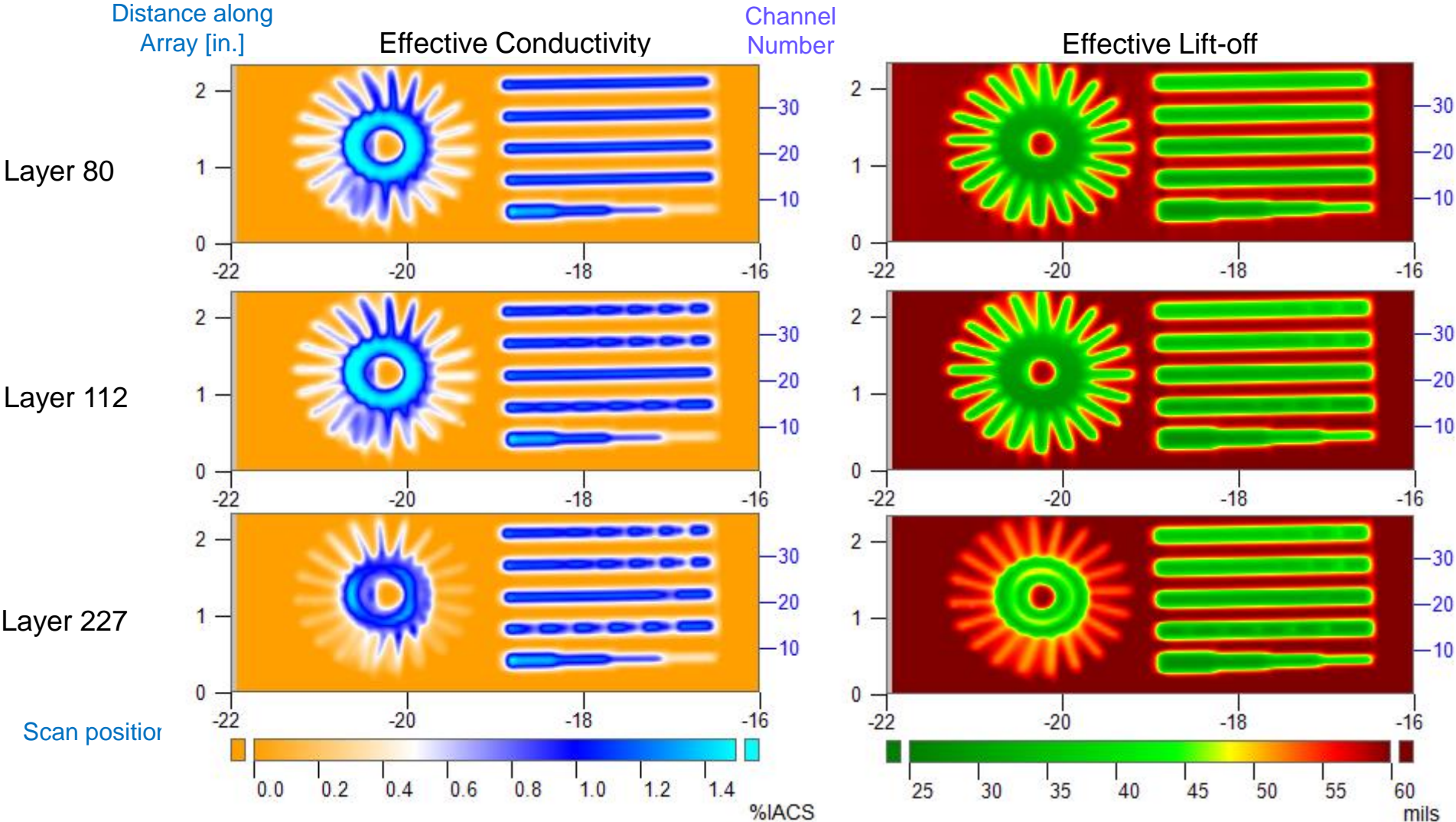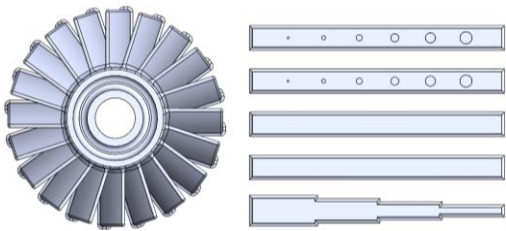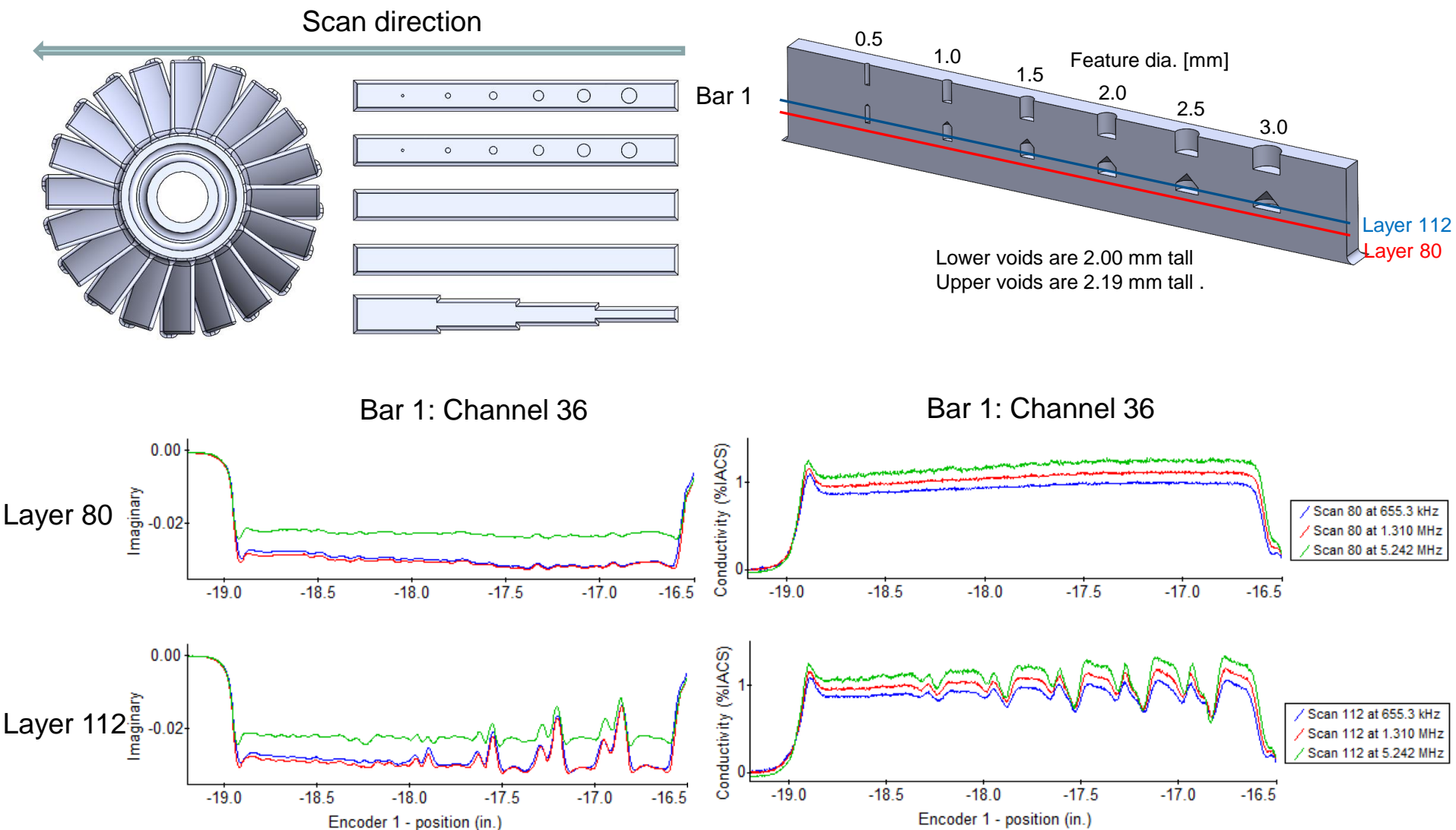
Void conditions visible – can use raw impedance data or effective property estimate data for analysis.
Effective properties most useful when the geometry is modeled

Example 1: B-Scan Plots for Z-direction (1)

Scan direction

Feature dia. [mm]

0.5
1.0
1.5
2.0
2.5
3.0

Increasing Layer Number

Bar 1

Bar 1: Channel 36, 1.5 mm dia. voids
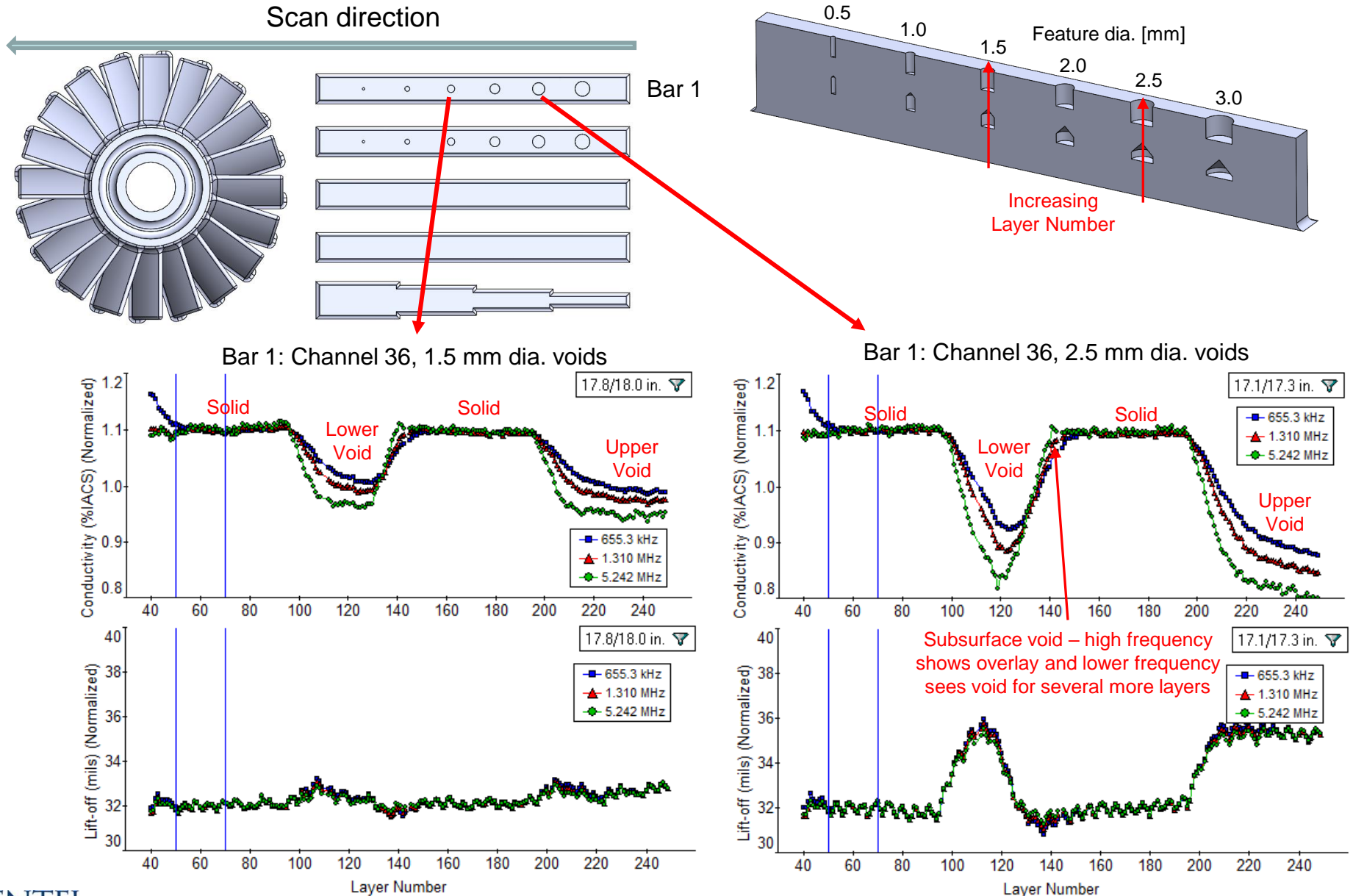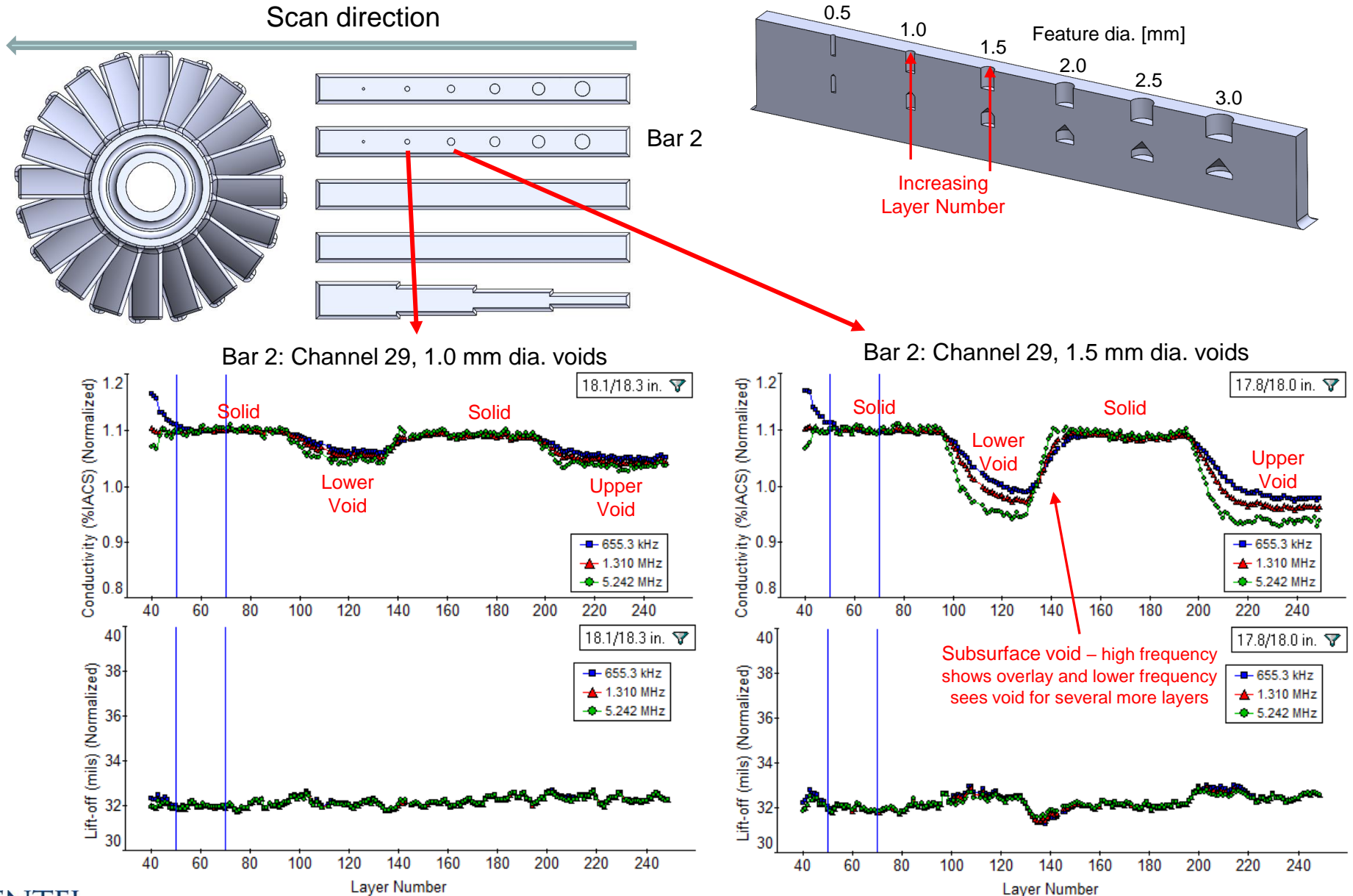
Solid   Solid

Lower Void   Upper Void

17.8/18.0 in.

- 655.3 kHz
- 1.310 MHz
- 5.242 MHz

17.8/18.0 in.

- 655.3 kHz
- 1.310 MHz
- 5.242 MHz

Bar 1: Channel 36, 2.5 mm dia. voids

Solid   Solid

Lower Void   Upper Void

17.1/17.3 in.

- 655.3 kHz
- 1.310 MHz
- 5.242 MHz

Subsurface void – high frequency shows overlay and lower frequency sees void for several more layers

17.1/17.3 in.

- 655.3 kHz
- 1.310 MHz
- 5.242 MHz

Example 1: B-Scan Plots for Z-direction (2)

Scan direction

Bar 2

Feature dia. [mm]

0.5   1.0   1.5   2.0   2.5   3.0

Increasing Layer Number

Bar 2: Channel 29, 1.0 mm dia. voids

Solid   Solid

Lower Void   Upper Void

18.1/18.3 in.

655.3 kHz
1.310 MHz
5.242 MHz

Conductivity (%IACS) (Normalized)

Lift-off (mils) (Normalized)

Layer Number

Bar 2: Channel 29, 1.5 mm dia. voids

Solid   Solid

Lower Void   Upper Void

17.8/18.0 in.

655.3 kHz
1.310 MHz
5.242 MHz

Subsurface void – high frequency shows overlay and lower frequency sees void for several more layers

Conductivity (%IACS) (Normalized)

Lift-off (mils) (Normalized)

Layer Number

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Example 2: B-Scan Plots

Scan direction

Feature dia. [mm]

0.04 0.08 0.16 0.40 0.80

Bar 3

Layer 120
Layer 80

1.2 1.4 1.6 1.8 2.0

Bar 4

Layer 120
Layer 80

All voids are 3mm in length.
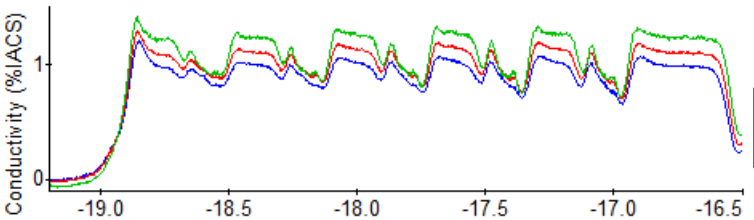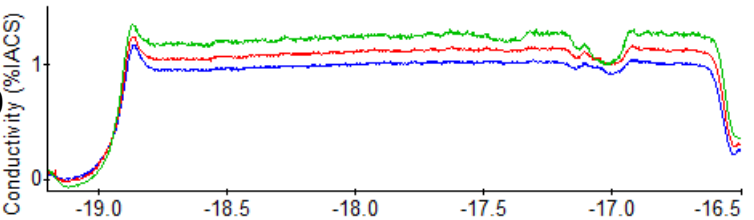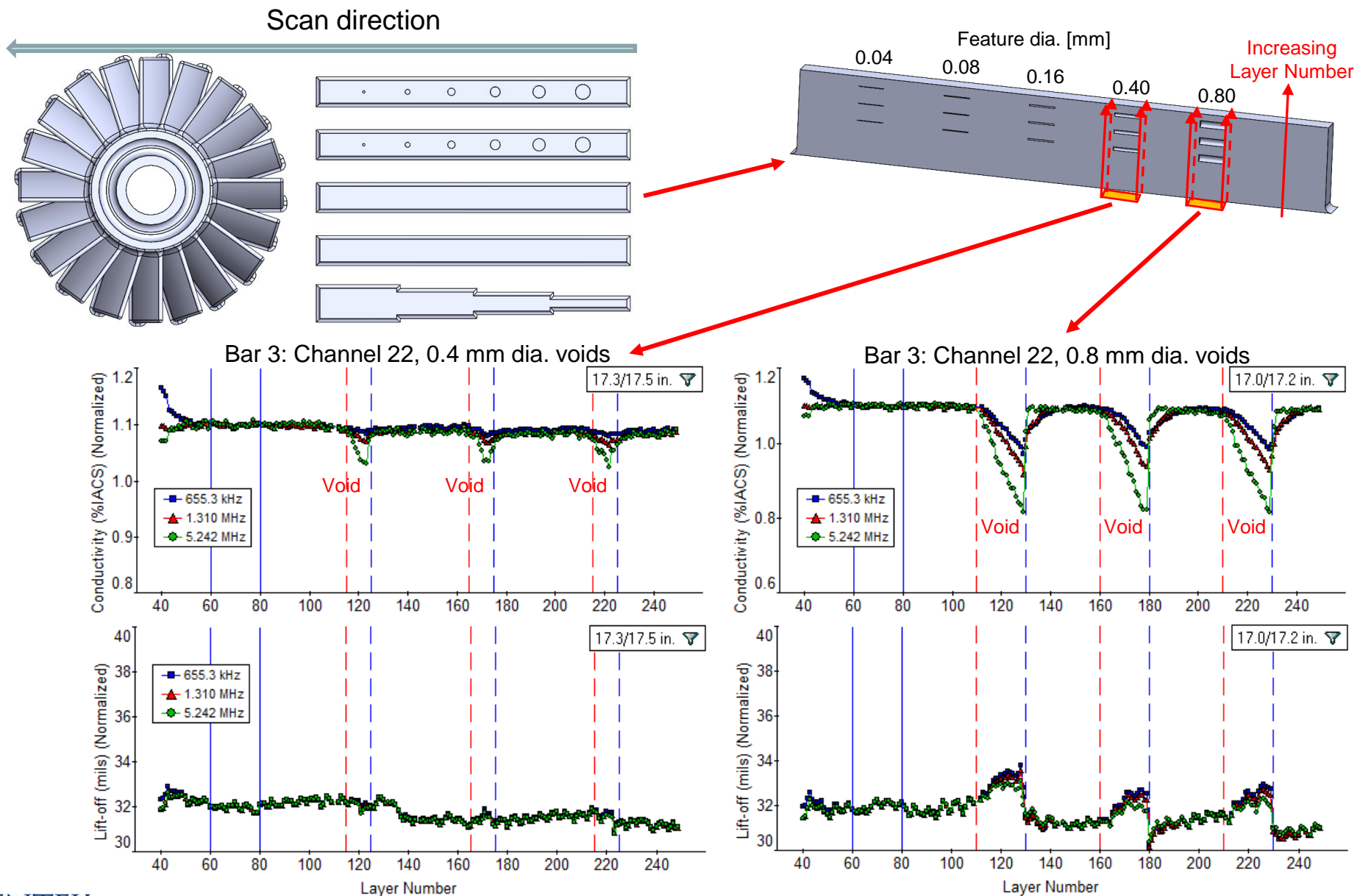
Bar 3: Channel 22

Bar 4: Channel 15

Layer 80

Layer 120

Scan 80 at 655.3 kHz
Scan 80 at 1.310 MHz
Scan 80 at 5.242 MHz

Scan 120 at 655.3 kHz
Scan 120 at 1.310 MHz
Scan 120 at 5.242 MHz

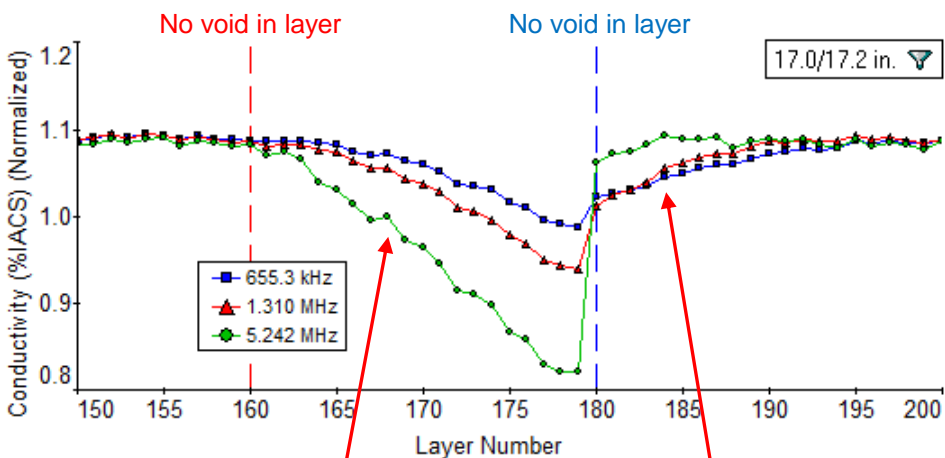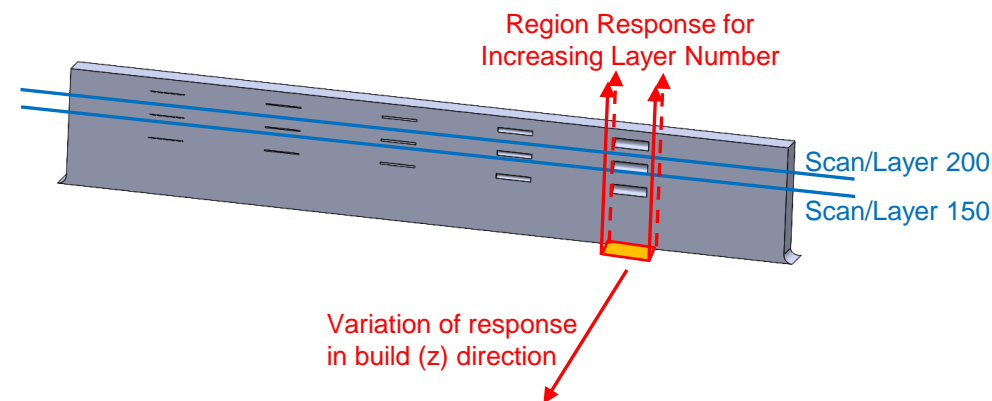Encoder 1 - position (in.)

Example 2: B-Scan Responses for Z-direction

Scan direction

Feature dia. [mm]

0.04　0.08　0.16　0.40　0.80

Increasing Layer Number

Bar 3: Channel 22, 0.4 mm dia. voids

Bar 3: Channel 22, 0.8 mm dia. voids

Example 2: B-Scan Plots (bar 3)

Nominal response over region associated with 0.8 mm dia. void

Region Response for Increasing Layer Number

Scan/Layer 200

Scan/Layer 150

Variation of response in build (z) direction

Scan across (x) build region for each layer (typical scan response)

Bar 3: Channel 22, 5.24 MHz

No void in layer

No void in layer

17.0/17.2 in.

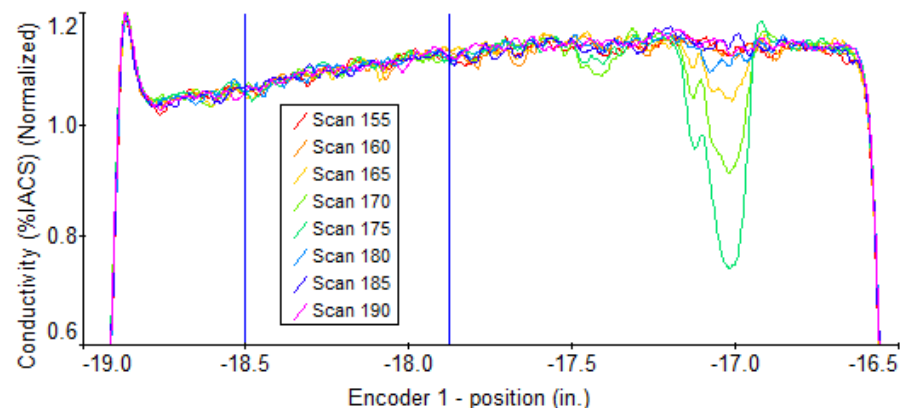- ■ 655.3 kHz
- ▲ 1.310 MHz
- ● 5.242 MHz

Surface-breaking void – for these layers all of the frequencies show the response to a surface breaking void

Subsurface void – high frequency shows void covered but lower frequencies see void for more layers

Scan 155
Scan 160
Scan 165
Scan 170
Scan 175
Scan 180
Scan 185
Scan 190

Bar 3: Channel 22, 655 kHz

Smaller voids may not form due to remelt/sintering

Scan 155
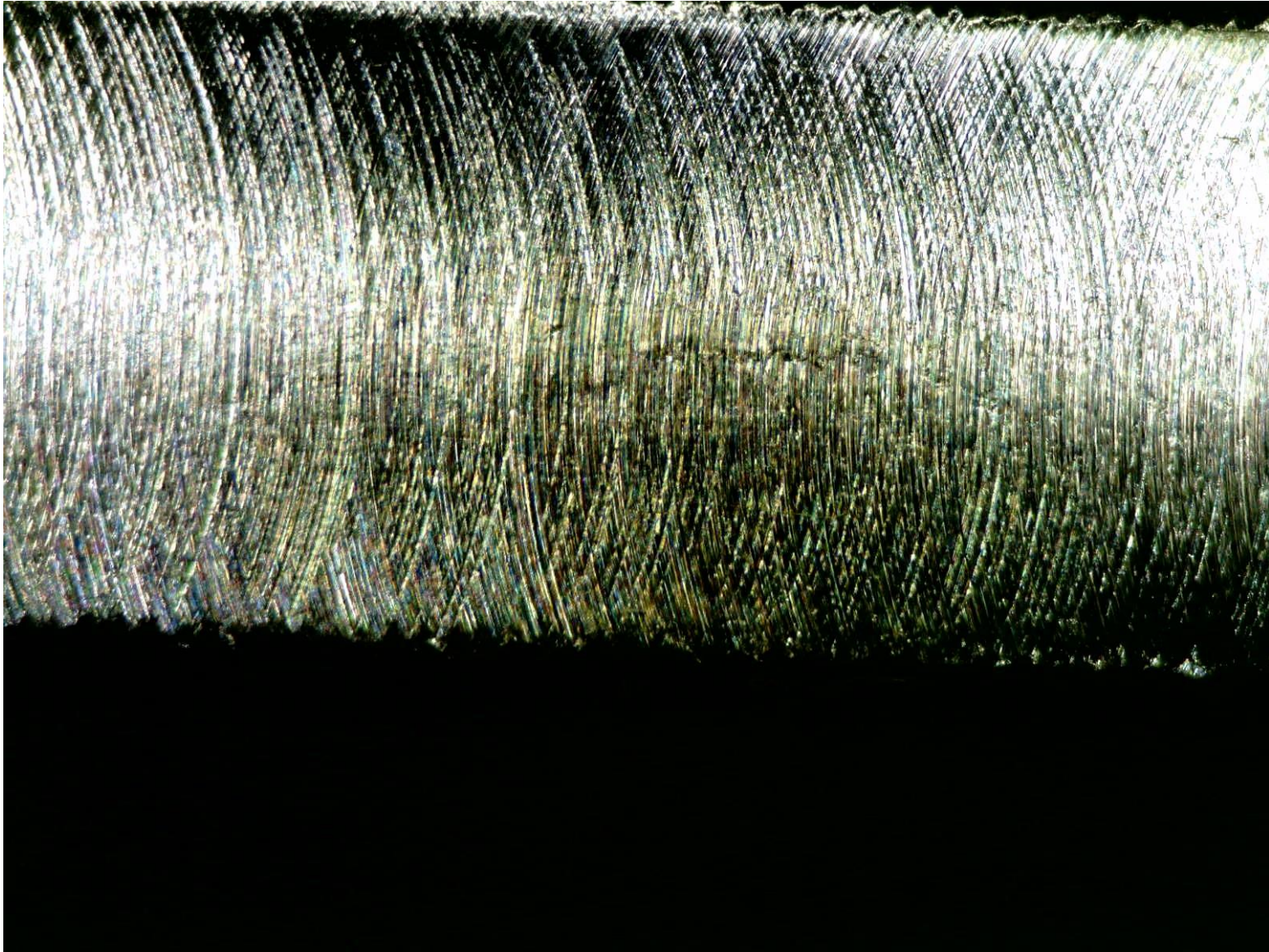Scan 160
Scan 165
Scan 170
Scan 175
Scan 180
Scan 185
Scan 190

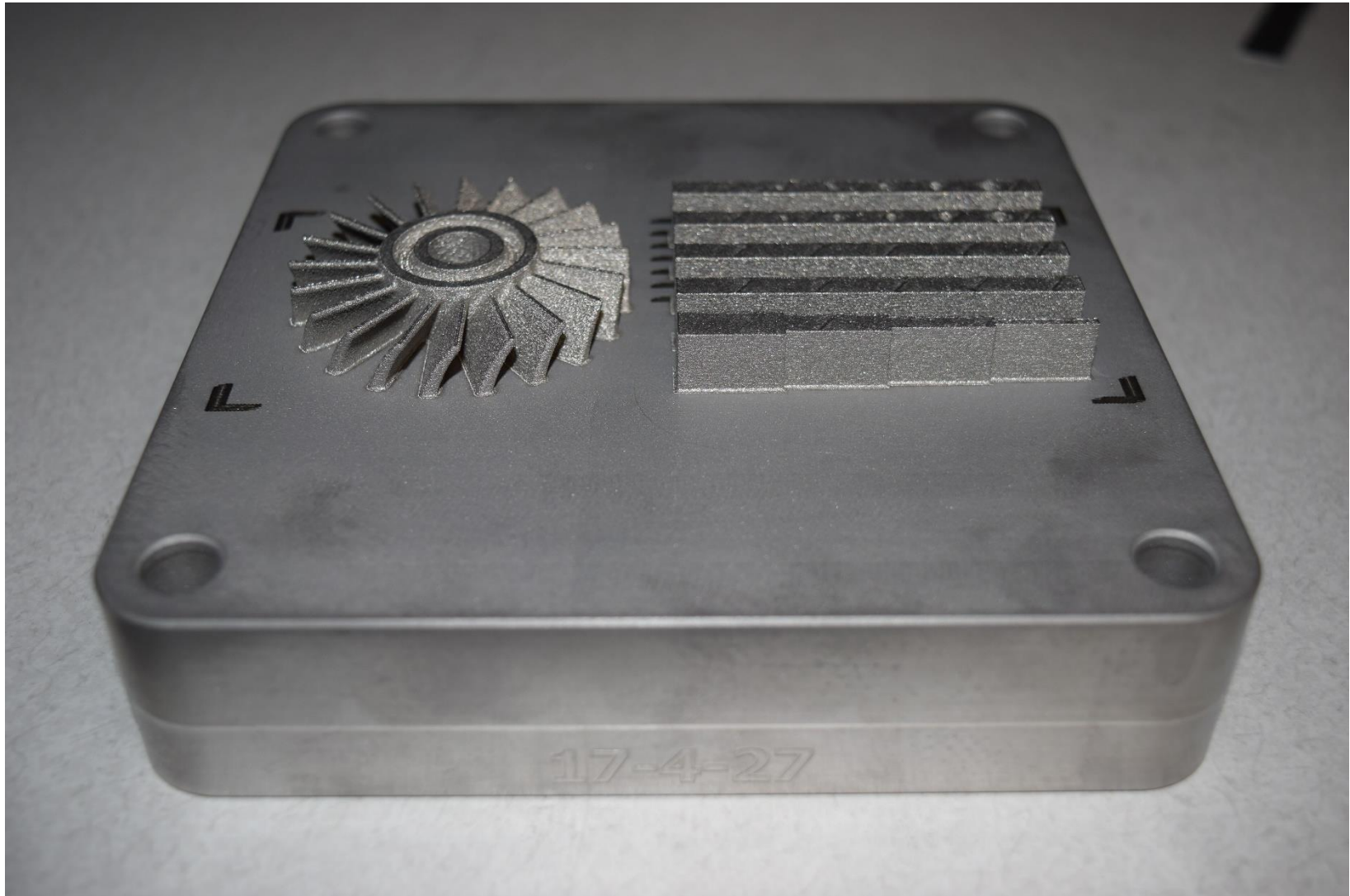JENTEK® Sensors, Inc.
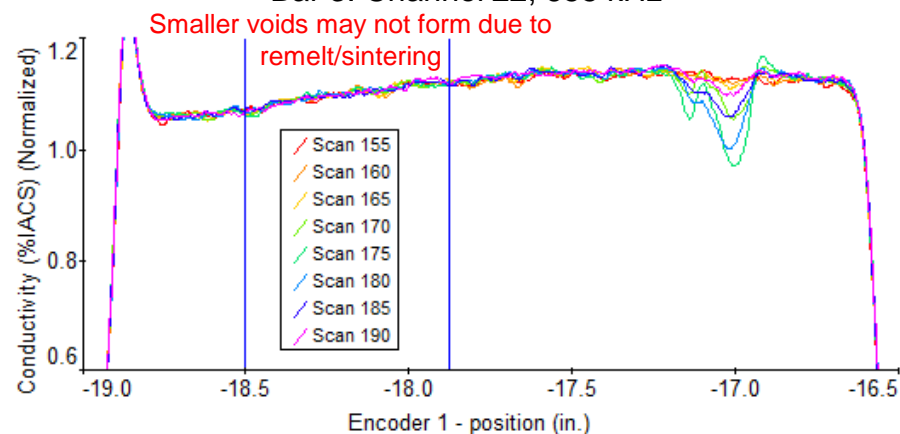
Lower Frequencies Detect Void Through More Layers
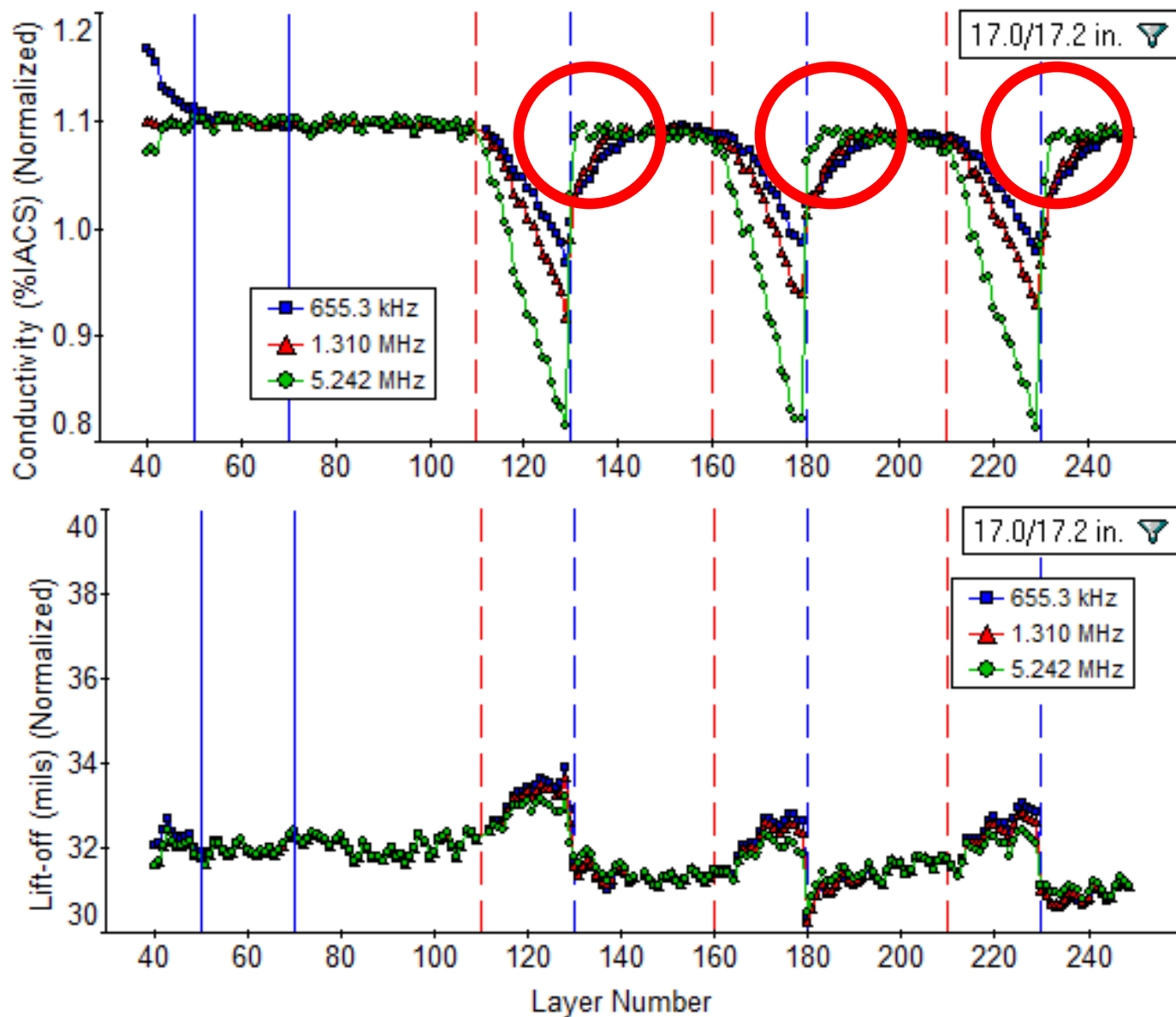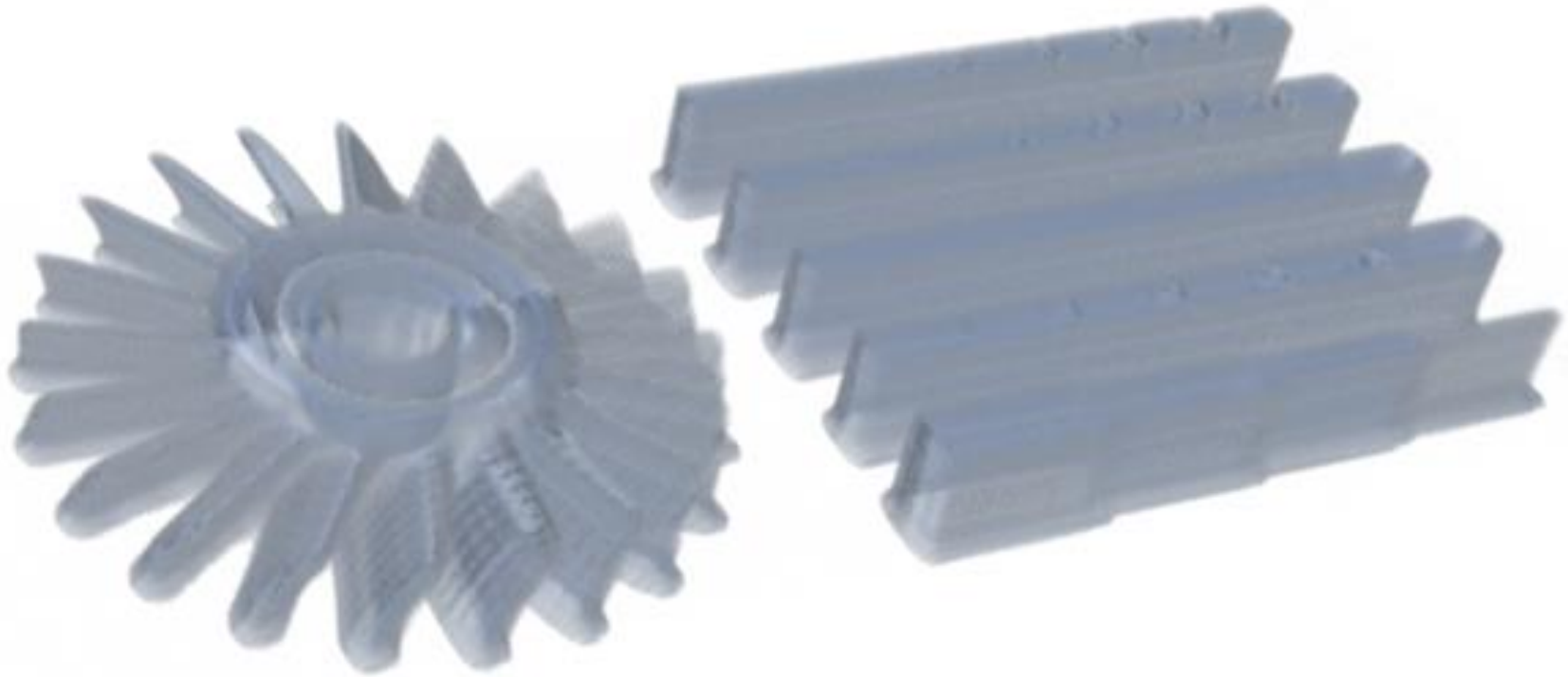
0.8 mm diameter void metallography

Photo of 249-layer Build (nickel alloy 718)

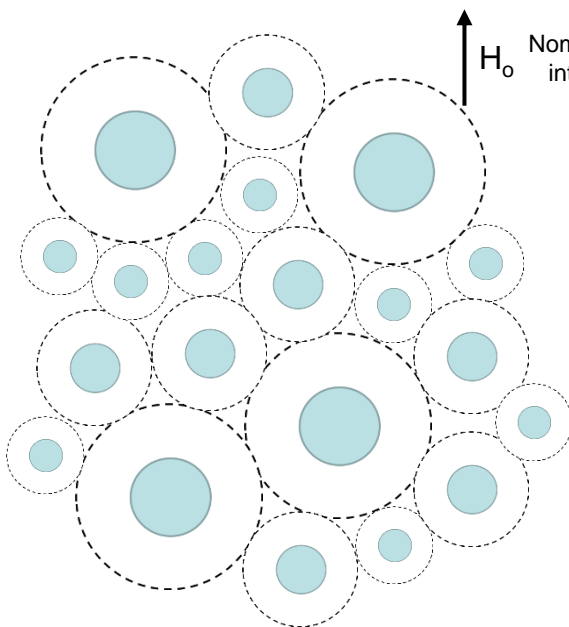# Preliminary Example Rendering of MWM-Array Data

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Powder Model (Composite Sphere Assemblage)

- Unpublished eddy current particle model extension spans low frequency (no eddy currents) to high frequency (thin skin depth compared to particle diameter) regimes
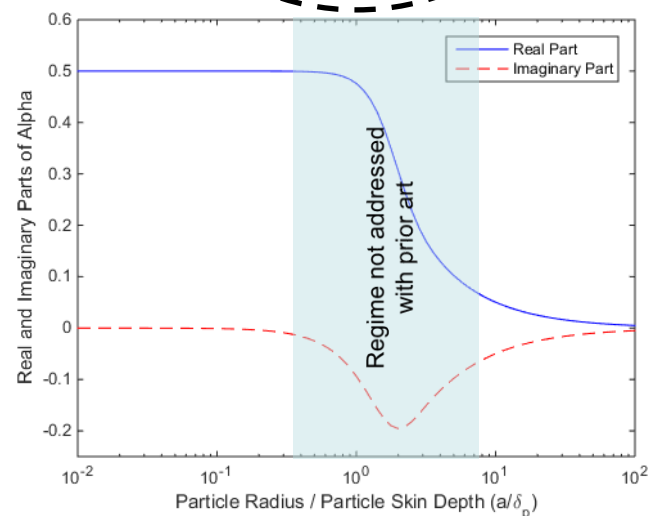

Sphere assemblage

H_o Nominal magnetic field intensity applied by sensor

Simplification for local field calculations

Single sphere model geometry H_o

Outside radius provide average distance where field reaches "average" field for each particle

b, a, z, x, μ_p, σ_p, μ_m, σ_m

Regime not addressed with prior art
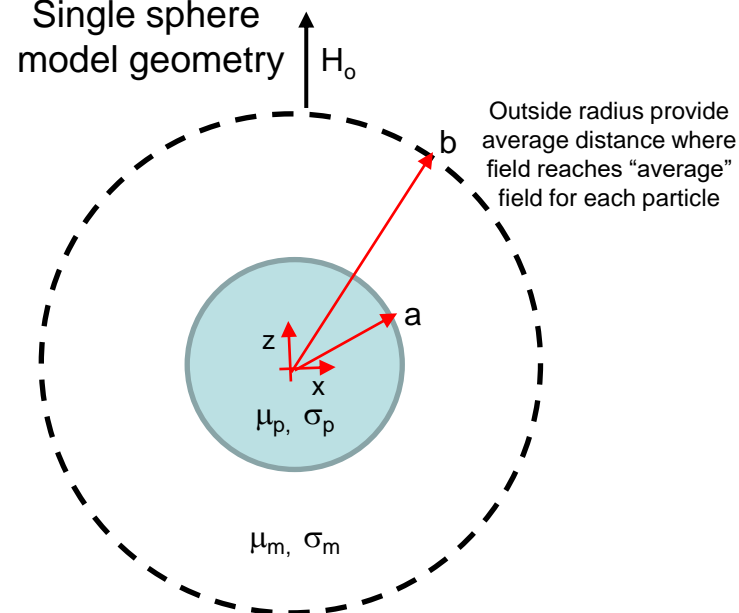
Powder Model – Example Predicted Responses

- New powder effective material property model exercised

- For target diameters of 30-100 um, frequencies of 1-20 MHz should be reasonable
  - Imaginary part of permeability shows powder responses at lower frequencies
  - Higher frequencies would be better for lower conductivity or smaller diameter powders
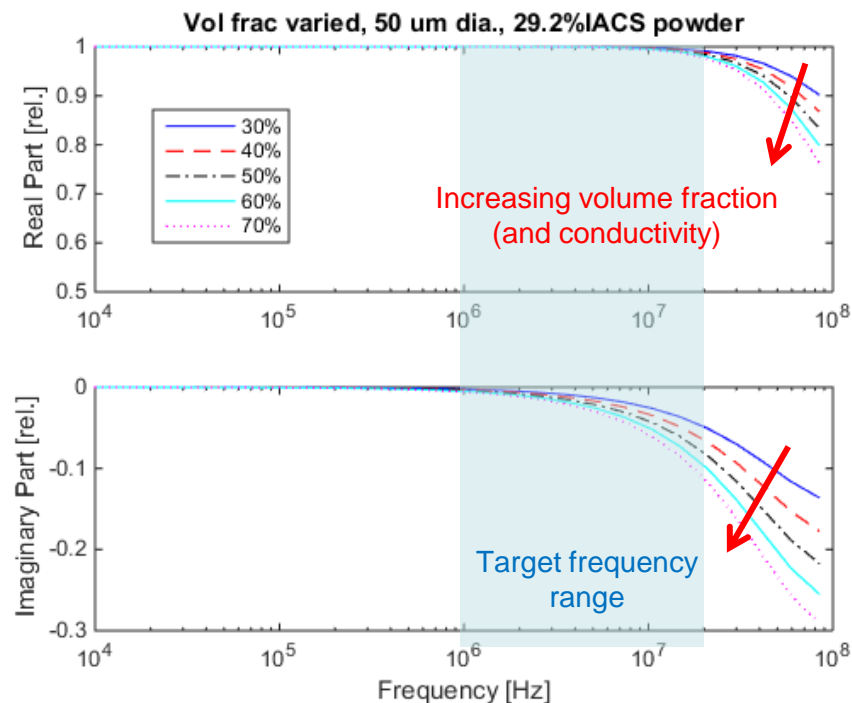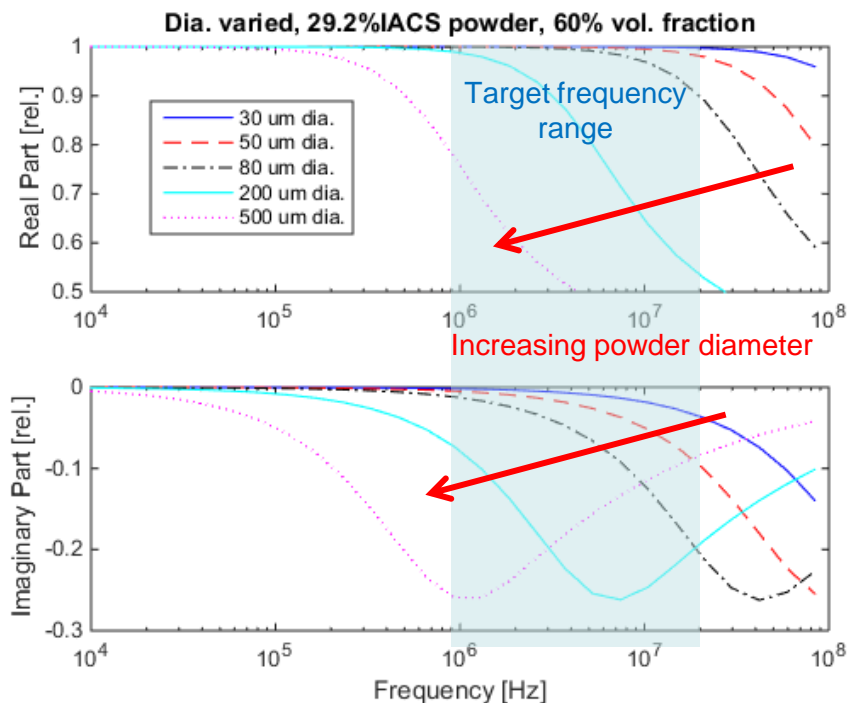
Sphere assemblage
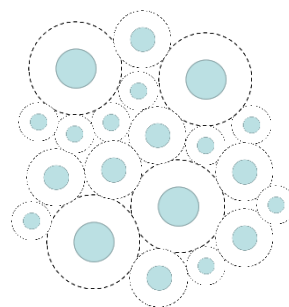
Layered Media Geometry

Powder (μ'_r, μ''_r, σ)

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

Dia. varied, 29.2%IACS powder, 60% vol. fraction

Target frequency range

- 30 um dia.
- 50 um dia.
- 80 um dia.
- 200 um dia.
- 500 um dia.

Increasing powder diameter

Vol frac varied, 50 um dia., 29.2%IACS powder

- 30%
- 40%
- 50%
- 60%
- 70%

Increasing volume fraction (and conductivity)

Target frequency range

Future Plans

- Larger channel count MWM-Arrays
- Larger channel count impedance instrumentation
- Improve ML/AI & preferred direction filtering support
- Machine agnostic installation
- Improve large data file handling
- Rapid data analytics including multithreading

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