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

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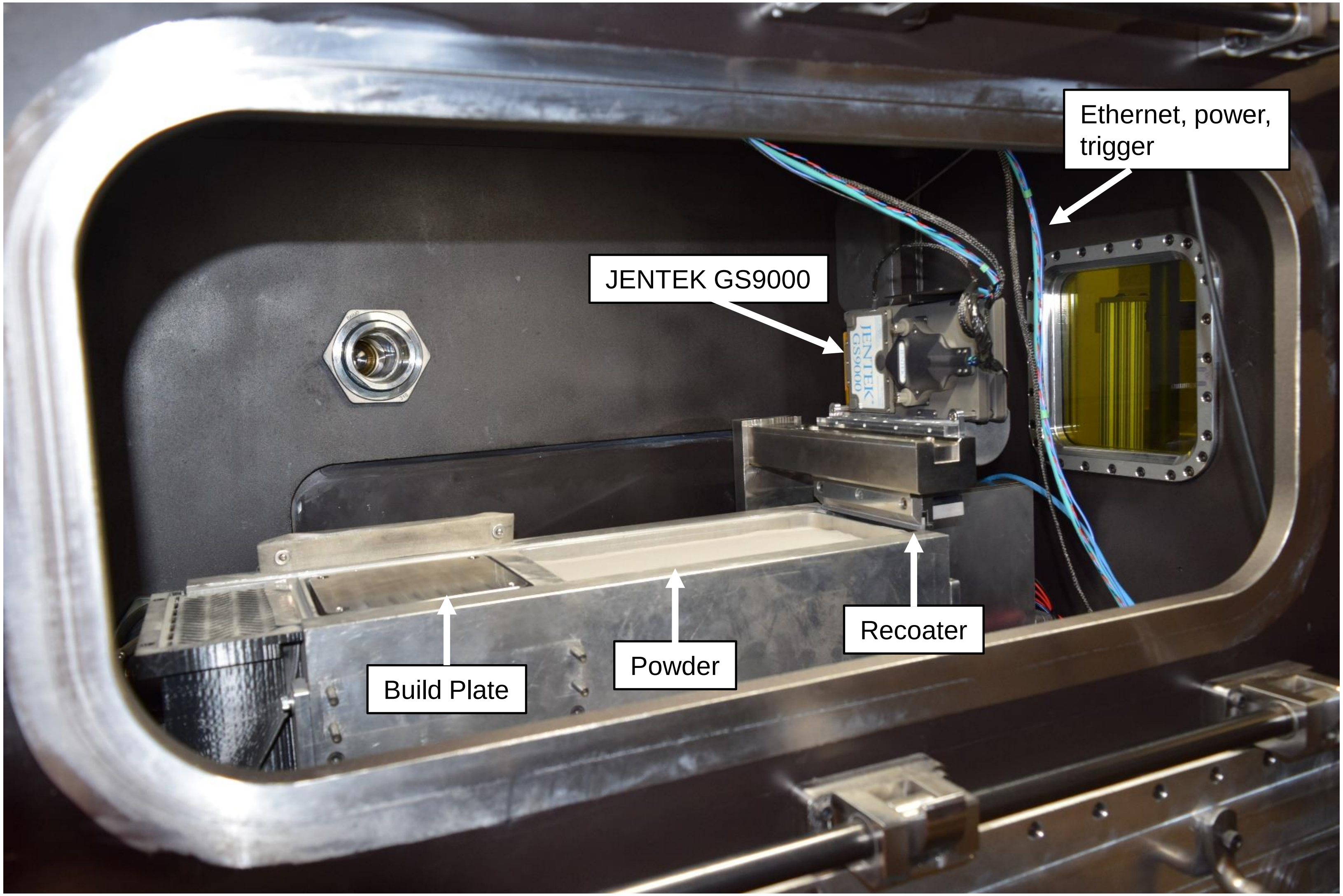
Abstract

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.

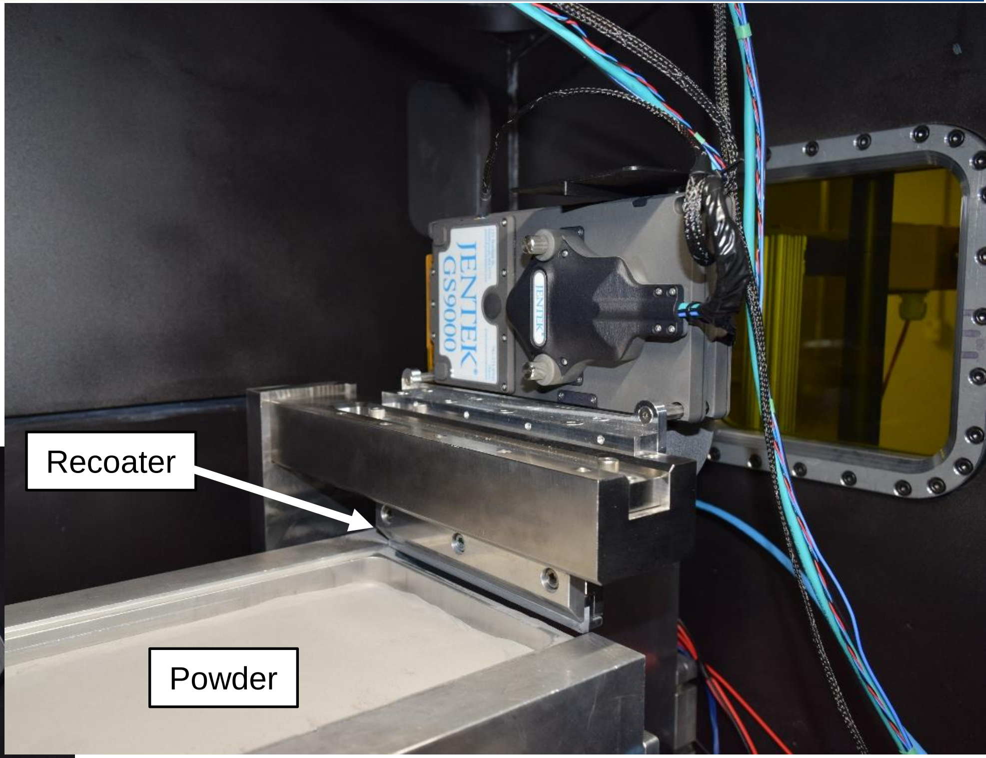
Agenda

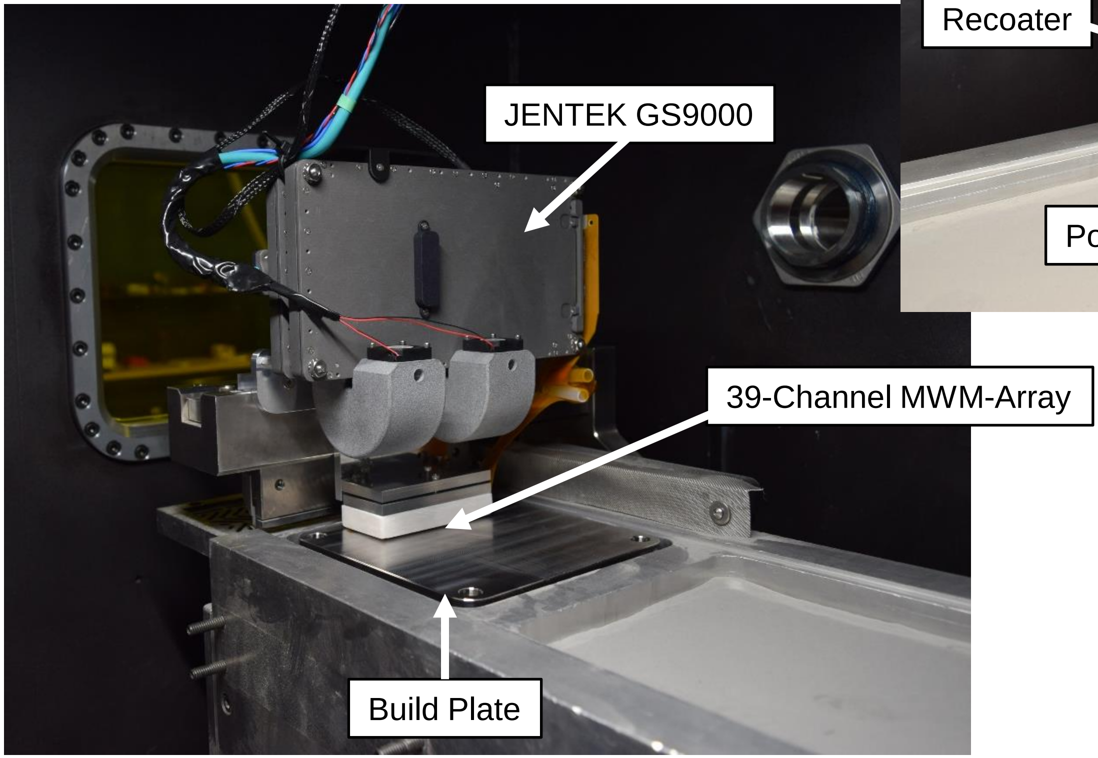
- Overview of installation and results
  - Installation details (machine, instrumentation, sensor, procedure)
  - Description of part build and defects
  - Example results
- Detailed eddy current array LPBF demo results
  - C-scan and B-scan images plots
  - Preferred direction (z-directed) filtering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

DART 2 System with GS9000 Installation

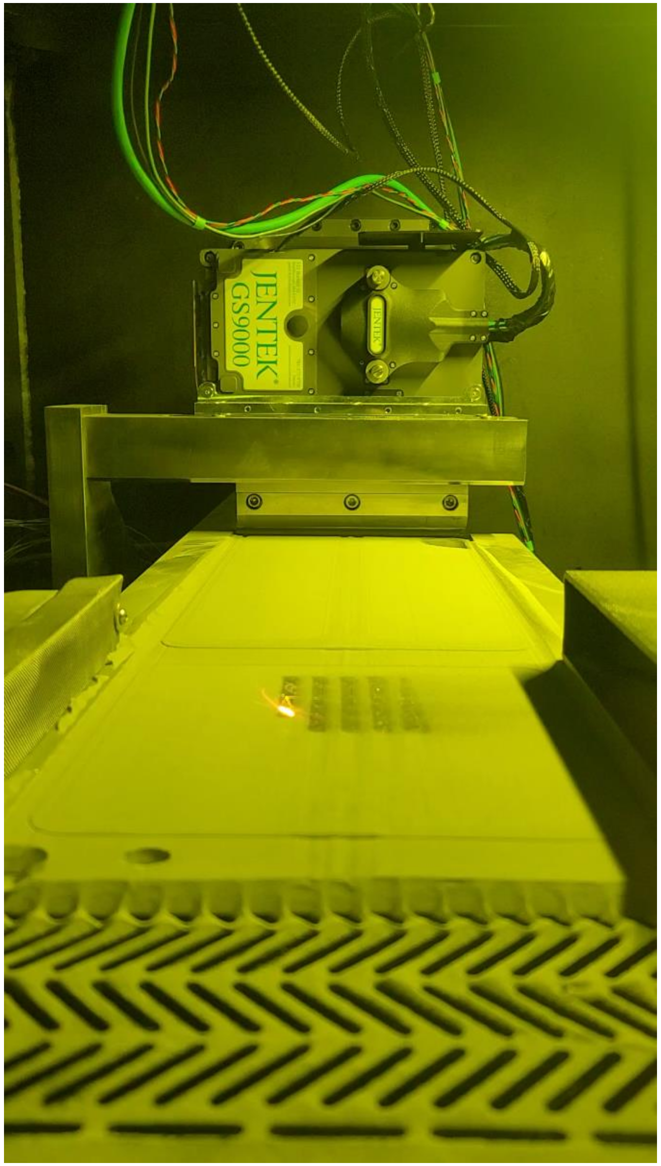


DART 2 System with GS9000 Installation



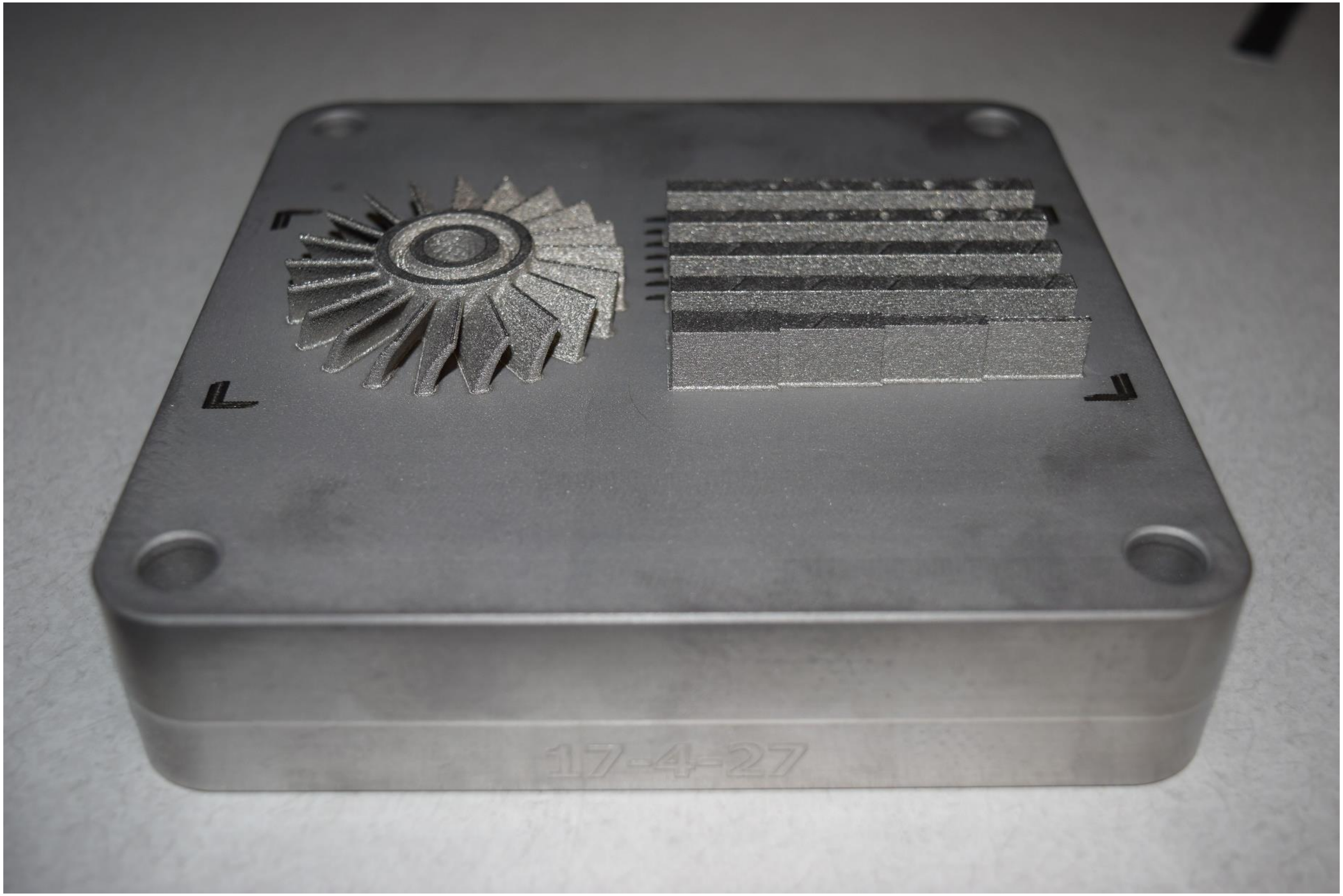


DART 2 System with GS9000 Installation (video)



CLICK HERE TO WATCH FULL VIDEO

Photo of 249-layer Build (nickel alloy 718)

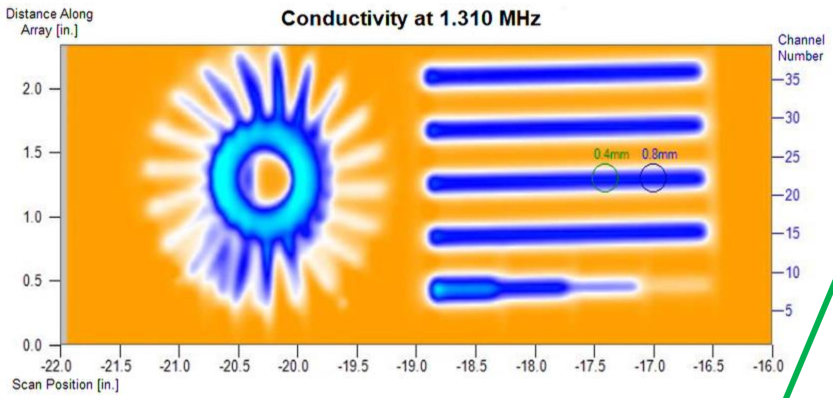


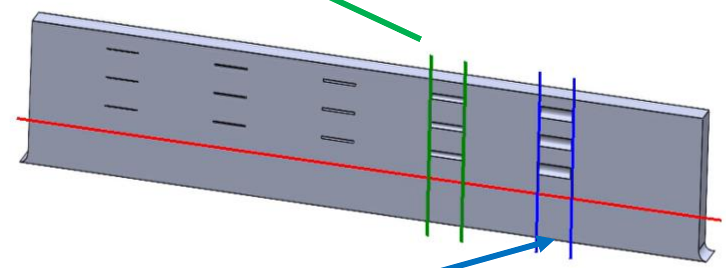
Conductivity C-scan and Z-directed Visualization

0.4 mm and 0.8 mm voids

CLICK TO WATCH FULL VIDEO

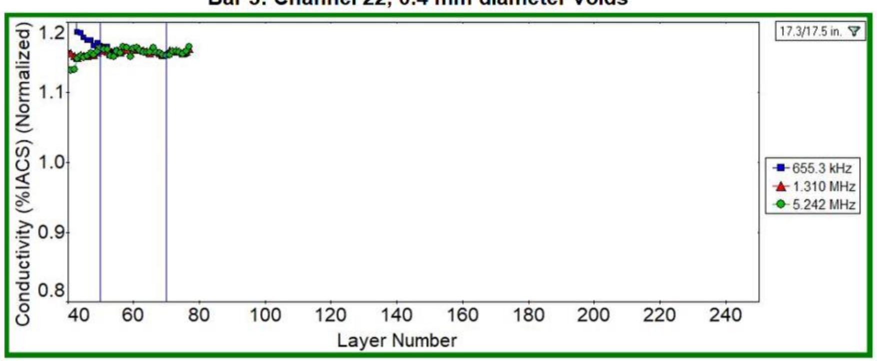
0.4 mm diameter, 3 mm long



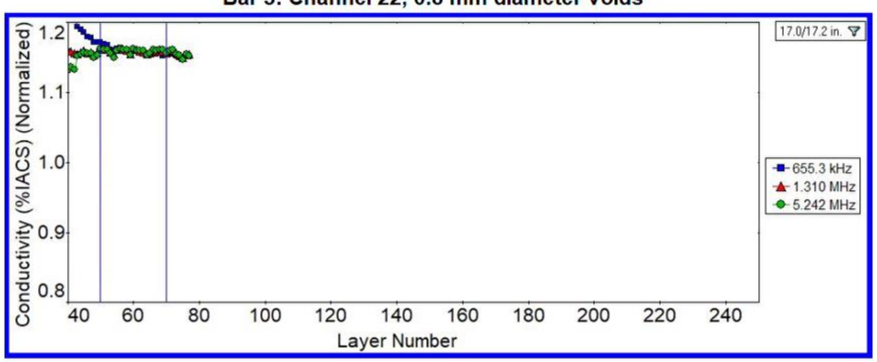


0.8 mm diameter, 3 mm long

Bar 3: Channel 22, 0.4 mm diameter voids

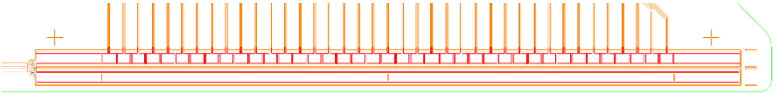


Bar 3: Channel 22, 0.8 mm diameter voids

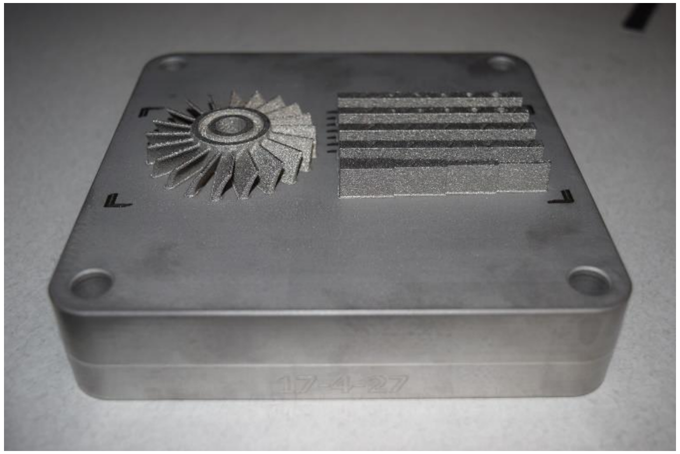


Note: %IACS = percent of International Annealed Copper Standard and 1%IACS = 0.58 MS/m

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)

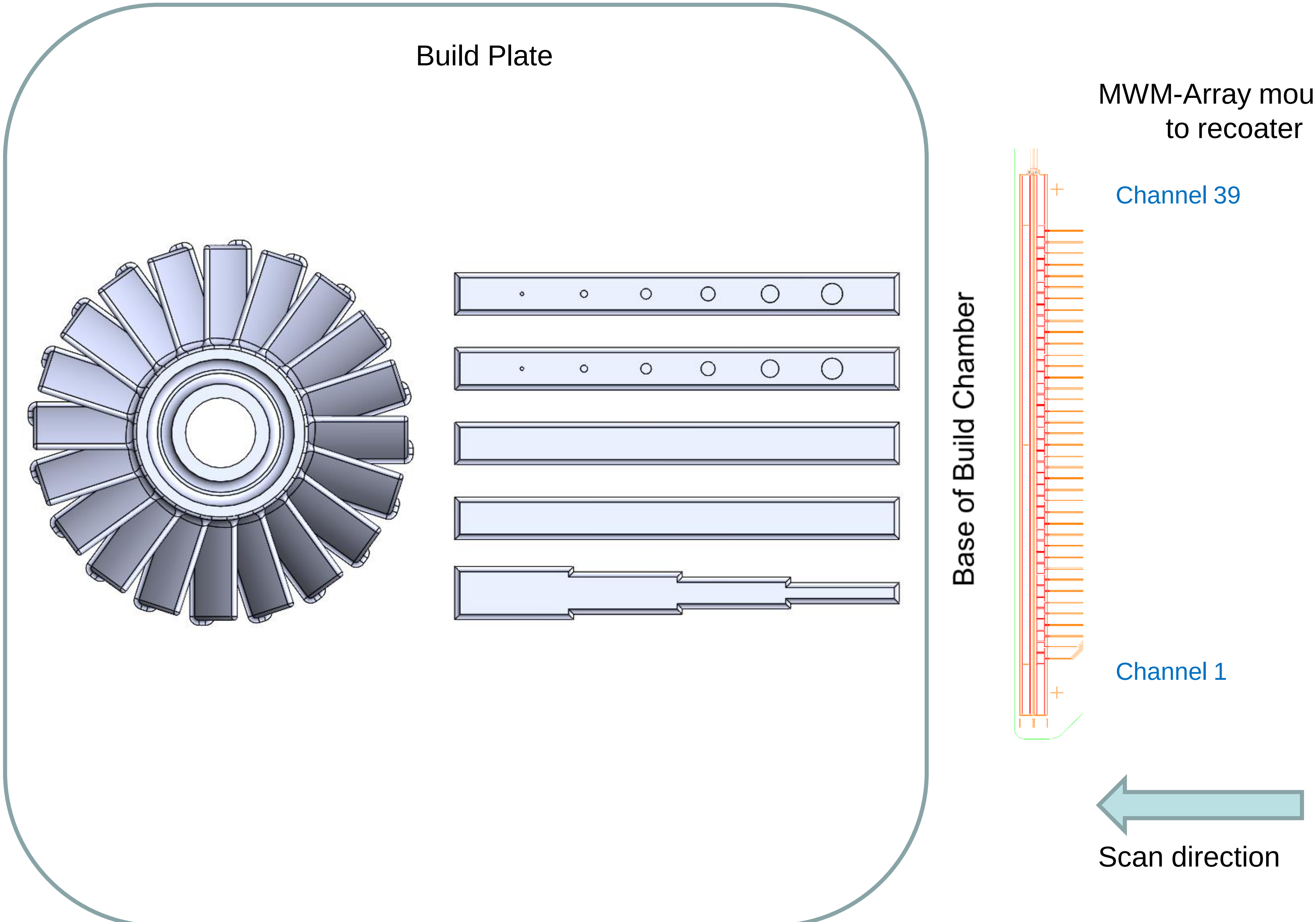


- Sensor array characteristics
  - MWM-Array: FA358
  - Sense element size: 1 x 1.5 mm [0.04 x 0.06 in.]
    - Can be as small as 0.75 x 0.75 mm [0.03 x 0.03 in.]
  - Scan width of MWM-Array: 59.4 mm [2.34 in.]
  - Number of channels: 39 (for this test but can be larger)

- 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.]

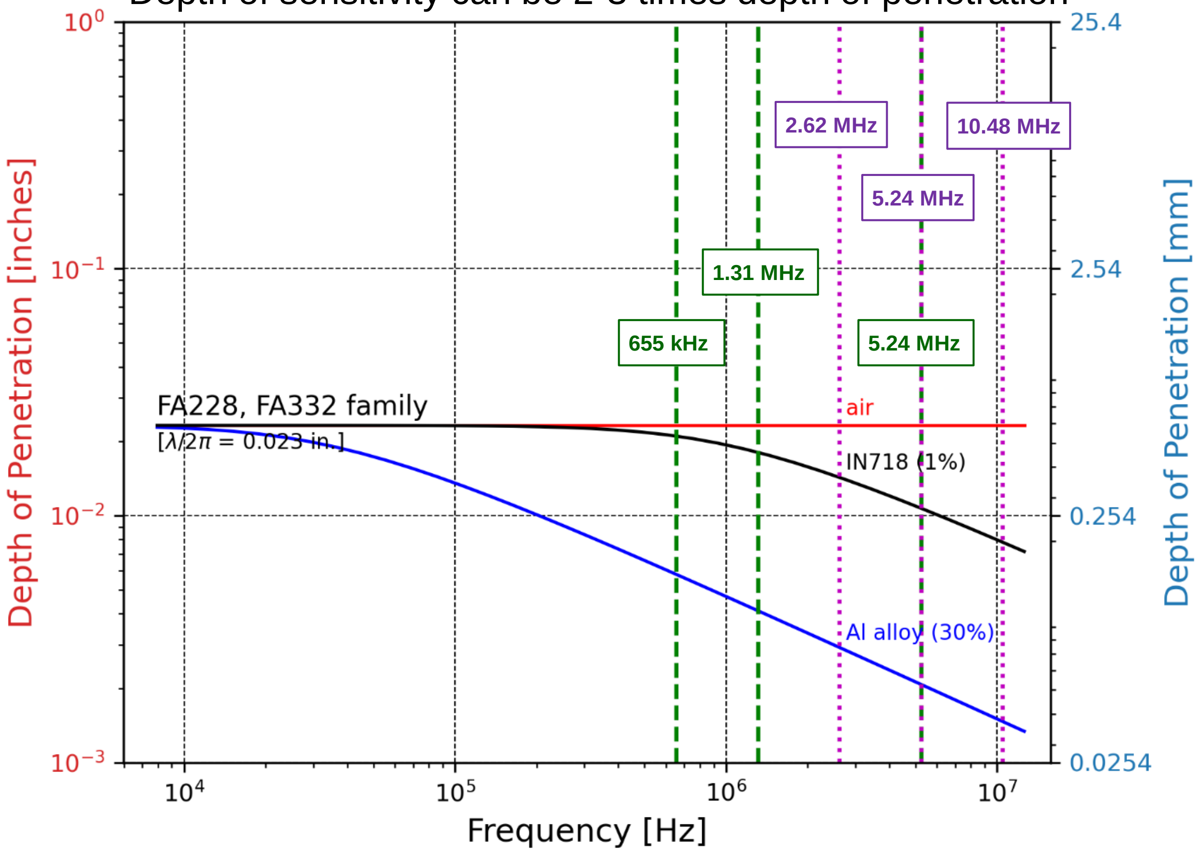
- Other
  - Calibration
    - Air calibrations performed with sensor array in air at start of build
    - Can recalibrate for each layer/scan (not used here)
  - File size: for 250 layers and 22 in. scan, 2.5 GB for raw and 5 GB including basic property estimates
    - Rough estimate is 45 MB per 100 layers per inspection inch for raw data for these typical settings

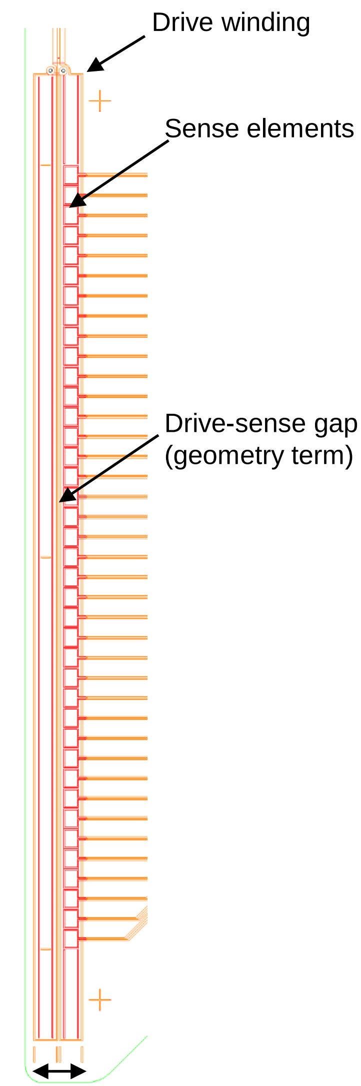
Build Nominal Geometry



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





Geometry limited

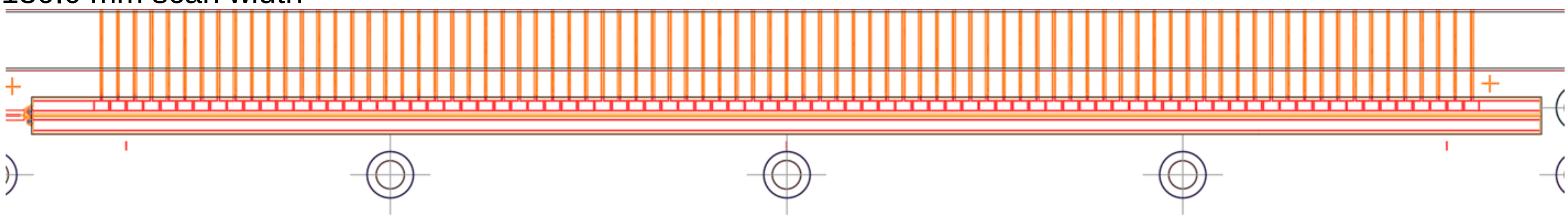
Affects the lift-off that can be tolerated

Skin depth limited

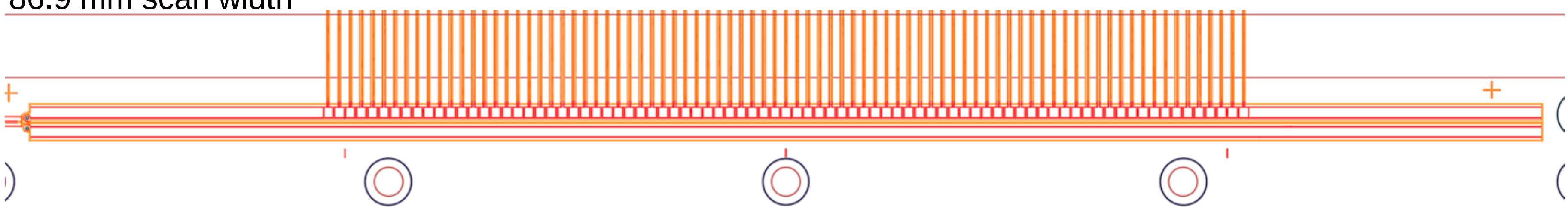
Primary factor affecting field penetration into the metallic material under test

Example JENTEK Sense Element Size Options

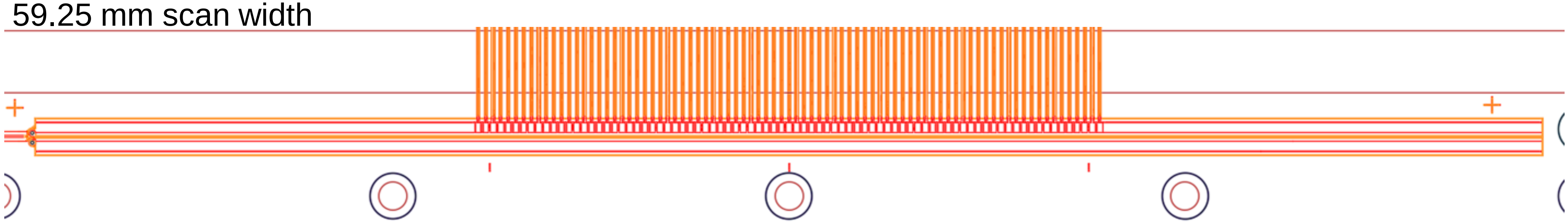
FA332 (for comparison)
1.65 mm sense element
130.0 mm scan width



FA364
1.10 mm sense element
86.9 mm scan width



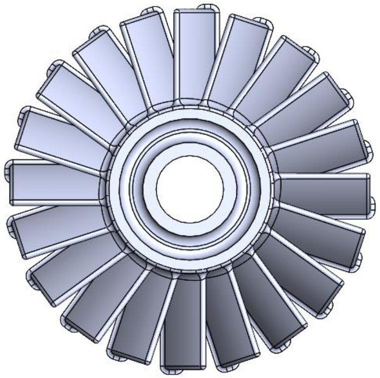
FA366
0.75 mm sense element
59.25 mm scan width



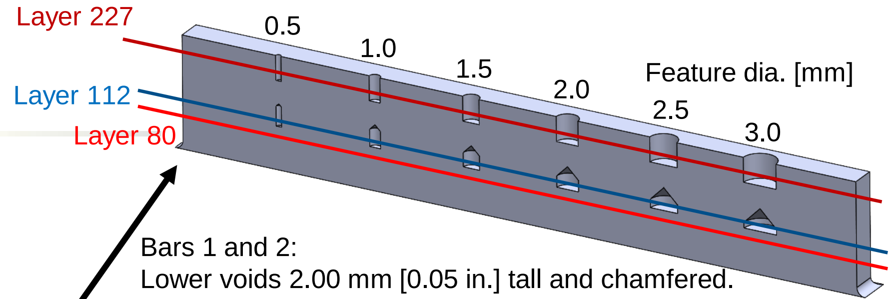
Build Geometry Model Details

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

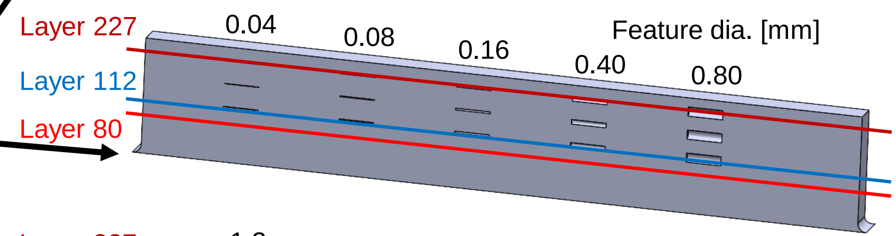
Example complex shaped part

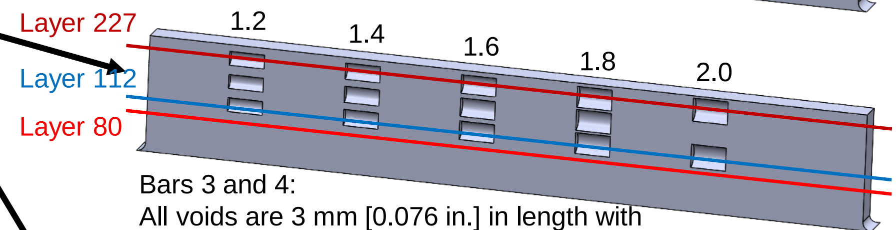


Each bar is 62 mm x 4.6 mm
[2.44 in x 0.180 in.]

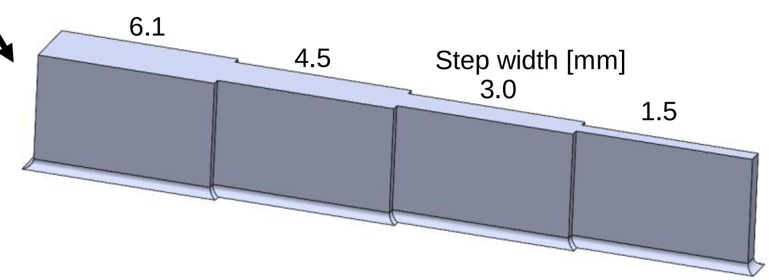


Bars 1 and 2:
Lower voids 2.00 mm [0.05 in.] tall and chamfered.
Upper voids 2.19 mm [0.056 in.] tall and surface breaking.
2 mm [0.05 in.] solid metal between upper and lower voids.

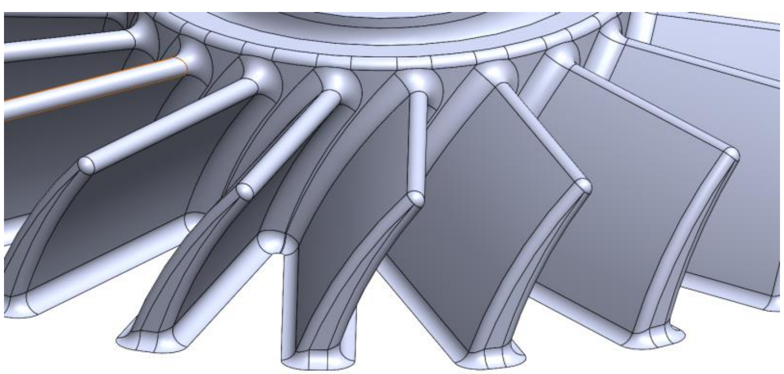




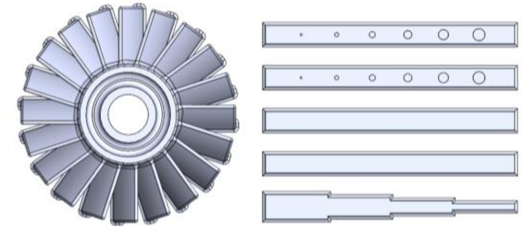
Bars 3 and 4:
All voids are 3 mm [0.076 in.] in length with
7 mm [0.180 in.] spacing.

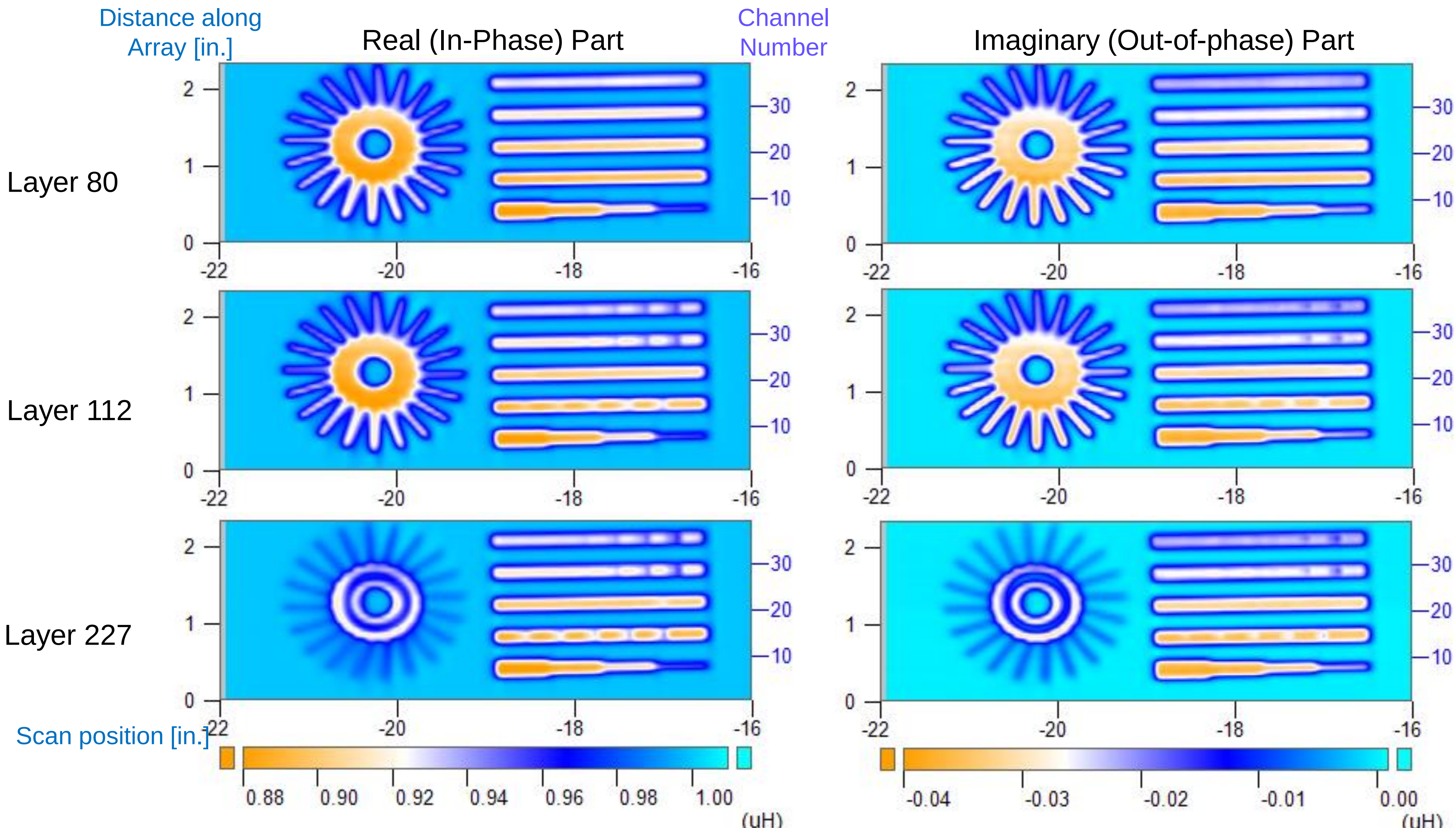


Bar 5: stepped taper. Each step is 15.5 mm [0.609 in.] long.

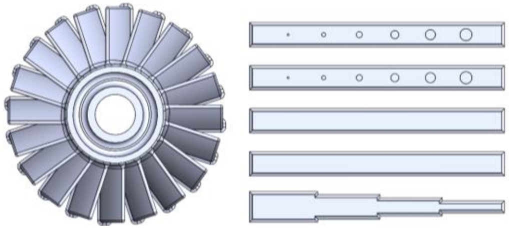


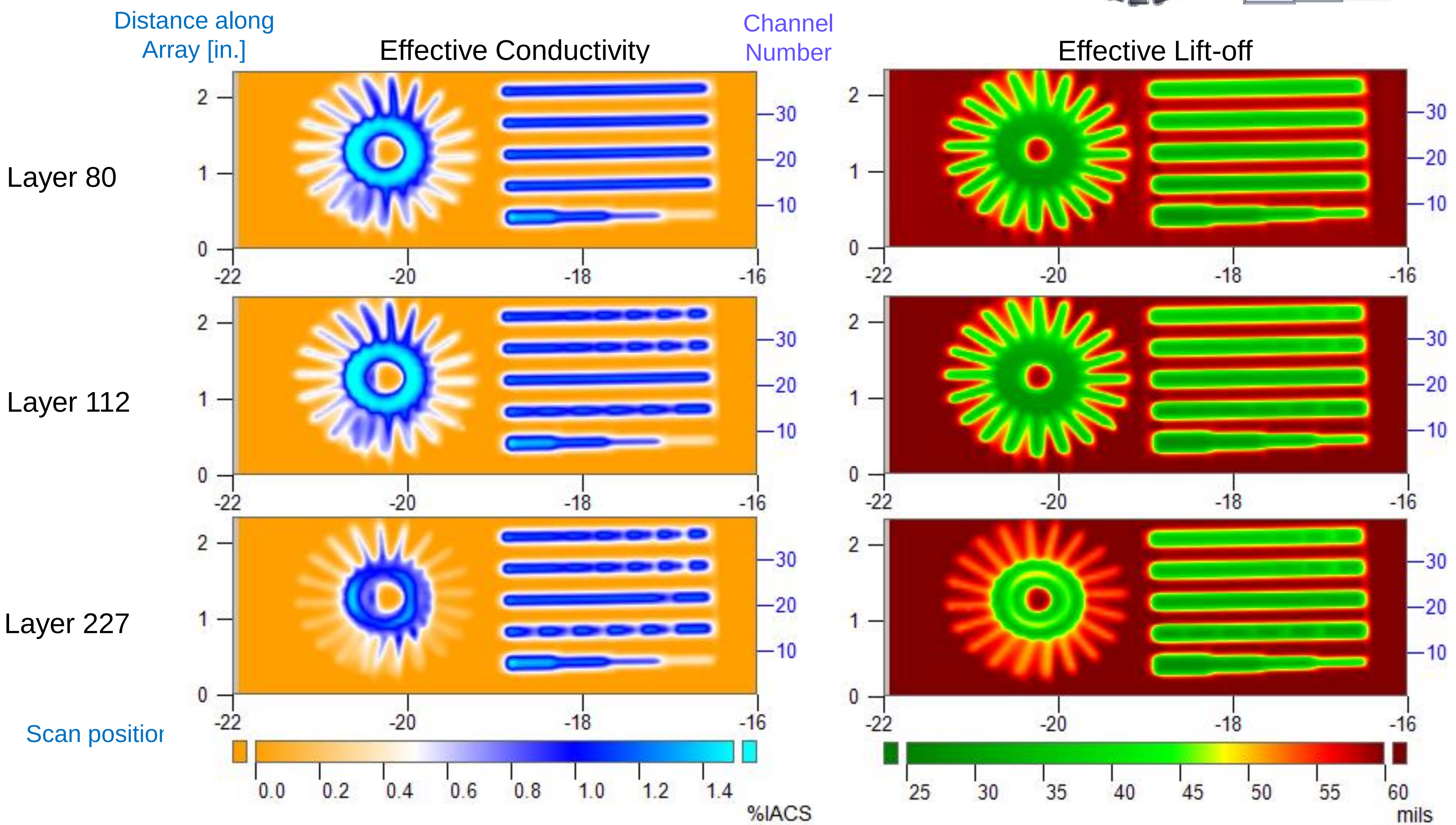
Example 5.24 MHz, Impedance Data





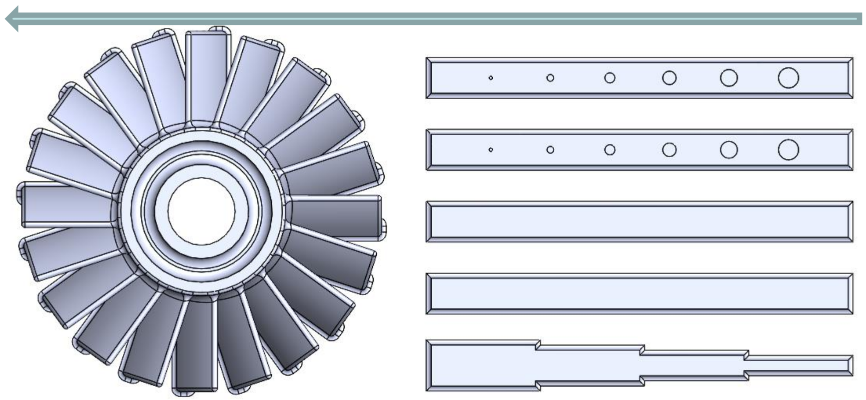
Example 5.24 MHz, Property Data



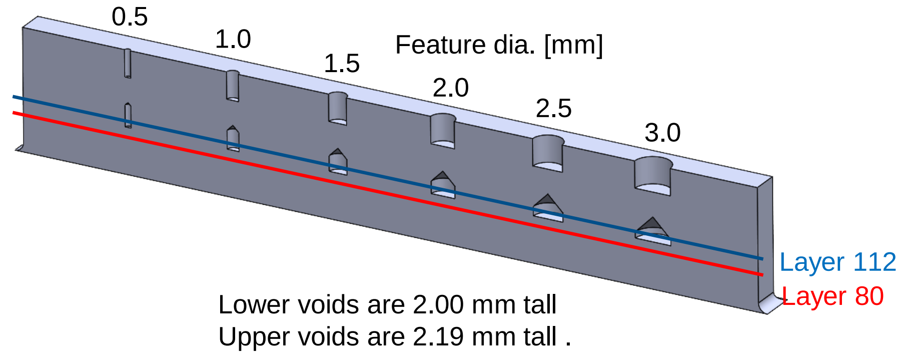


Example 1: B-Scan Plots

Scan direction



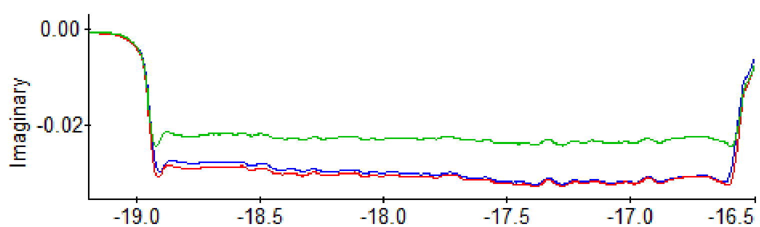
Bar 1

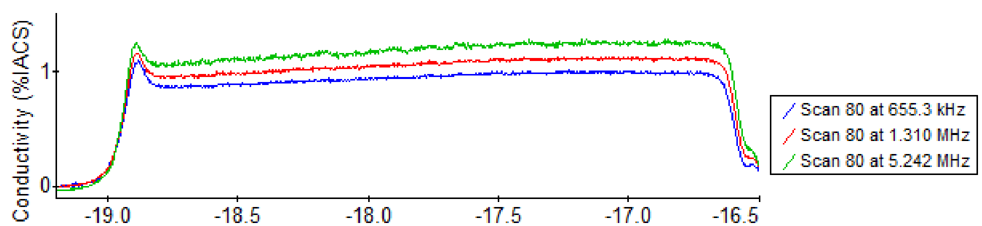


Bar 1: Channel 36

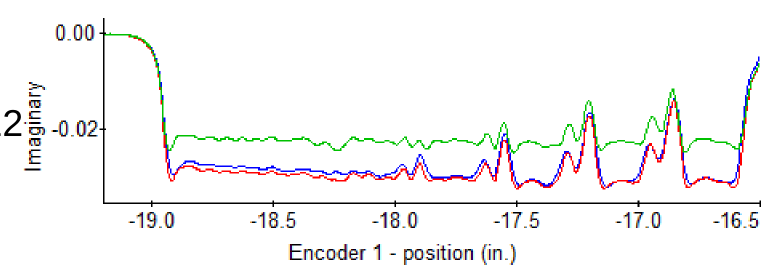
Bar 1: Channel 36

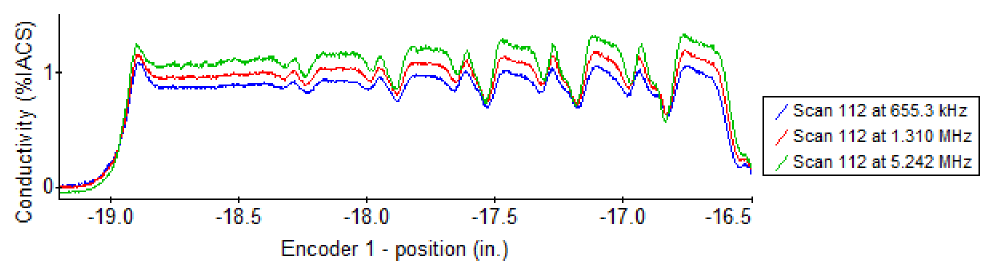
Layer 80





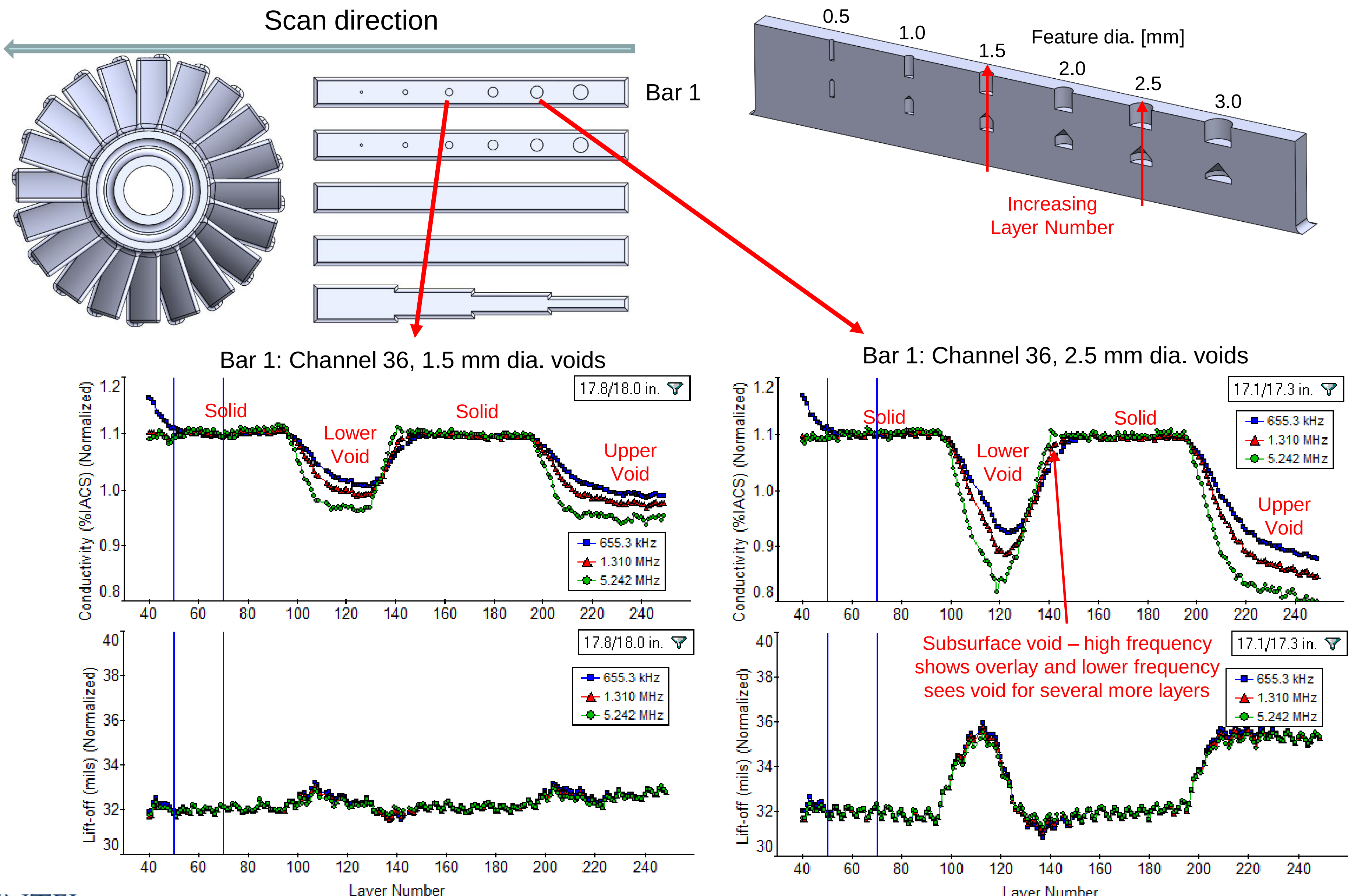
Layer 112





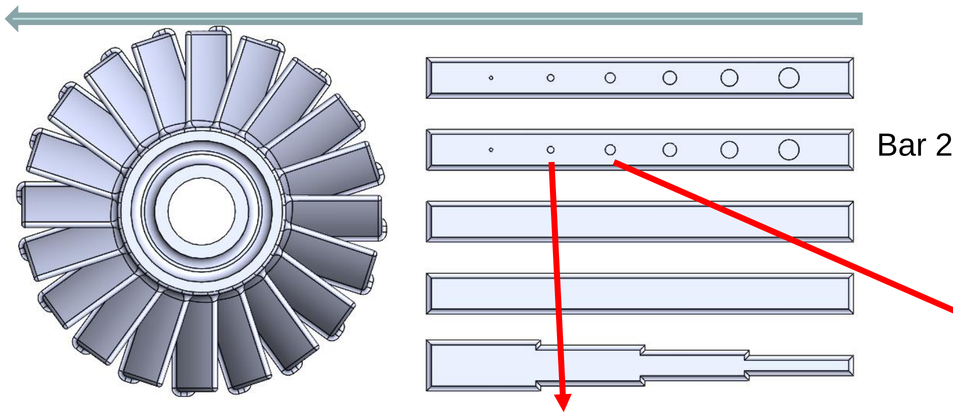
Void conditions visible – can use raw impedance data or effective property estimate data for analysis.
Effective properties most useful when the geometry is modeled

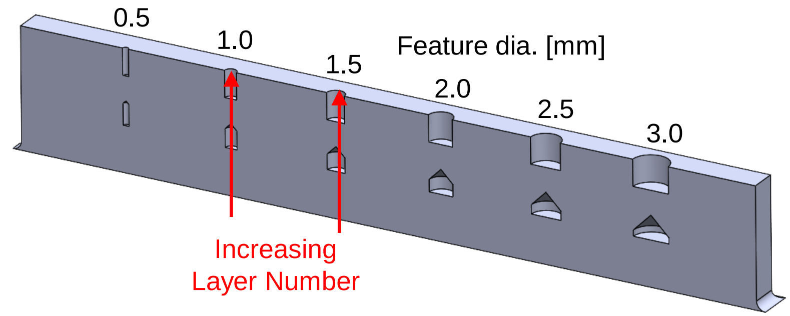
Example 1: B-Scan Plots for Z-direction (1)



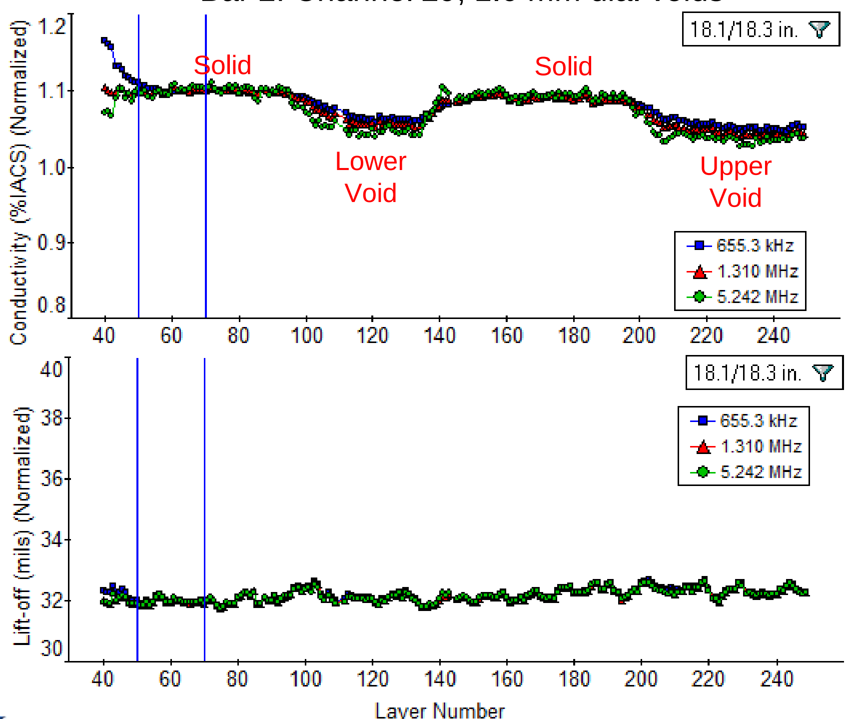
Example 1: B-Scan Plots for Z-direction (2)

Scan direction

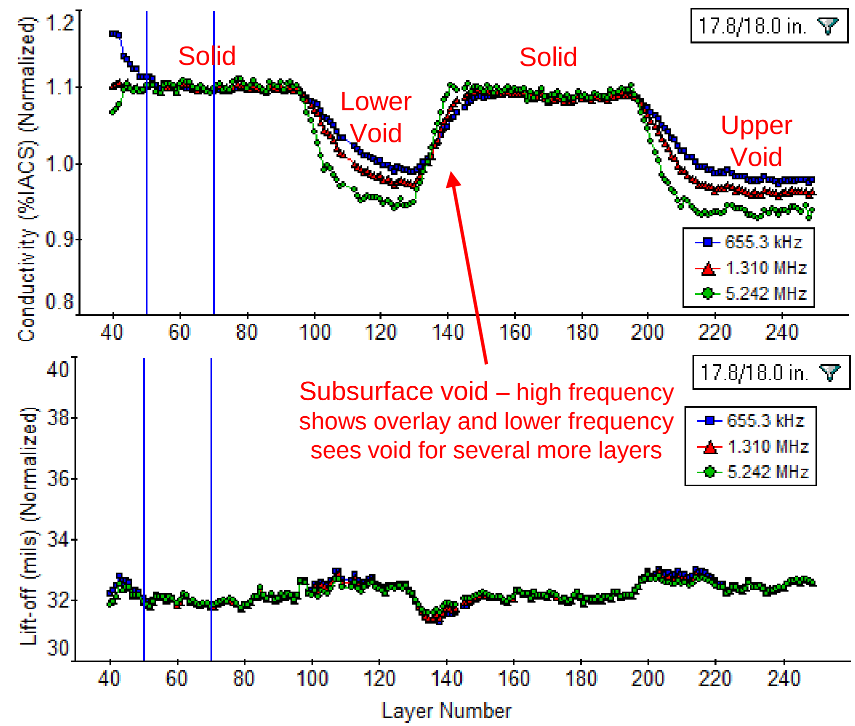




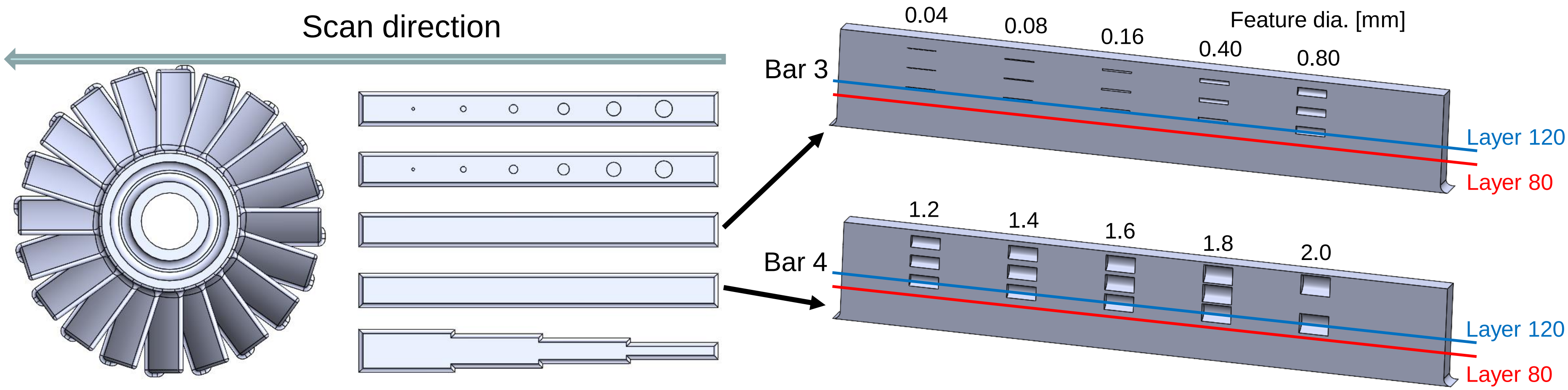
Bar 2: Channel 29, 1.0 mm dia. voids



Bar 2: Channel 29, 1.5 mm dia. voids



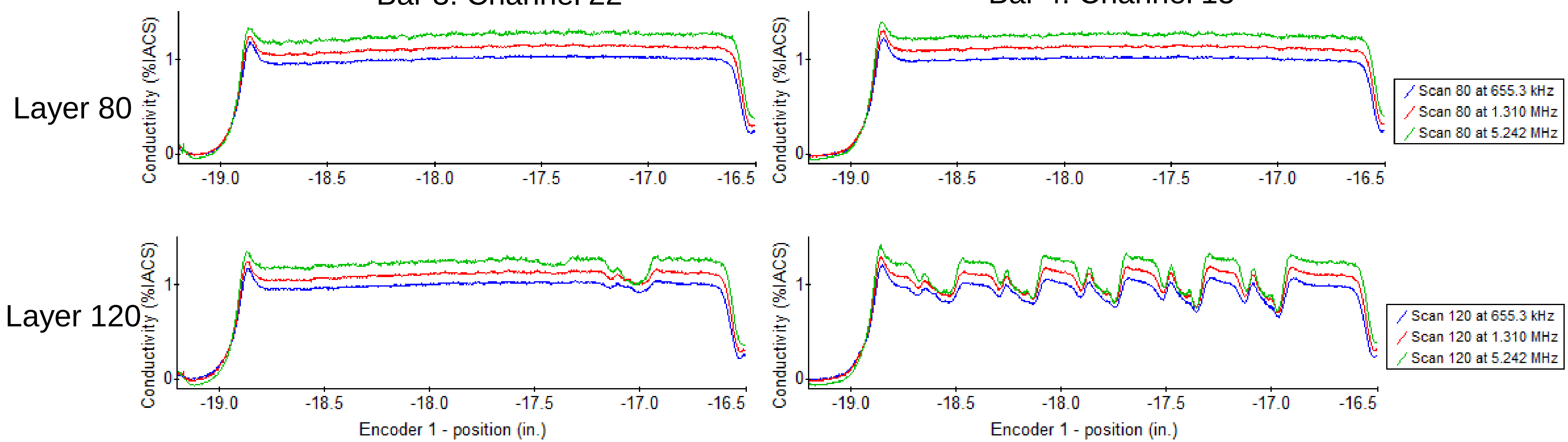
Example 2: B-Scan Plots



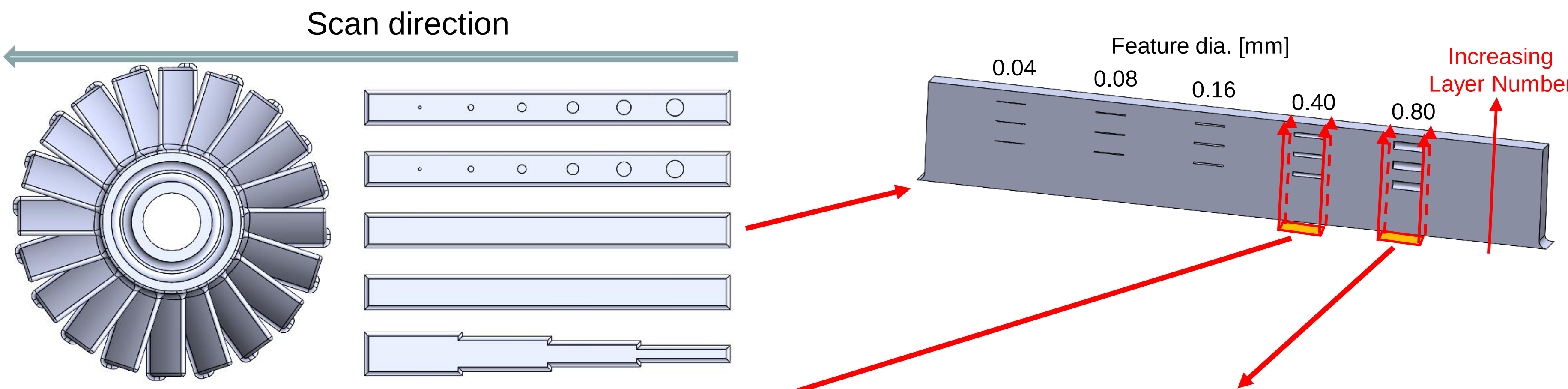
All voids are 3mm in length.

Bar 3: Channel 22

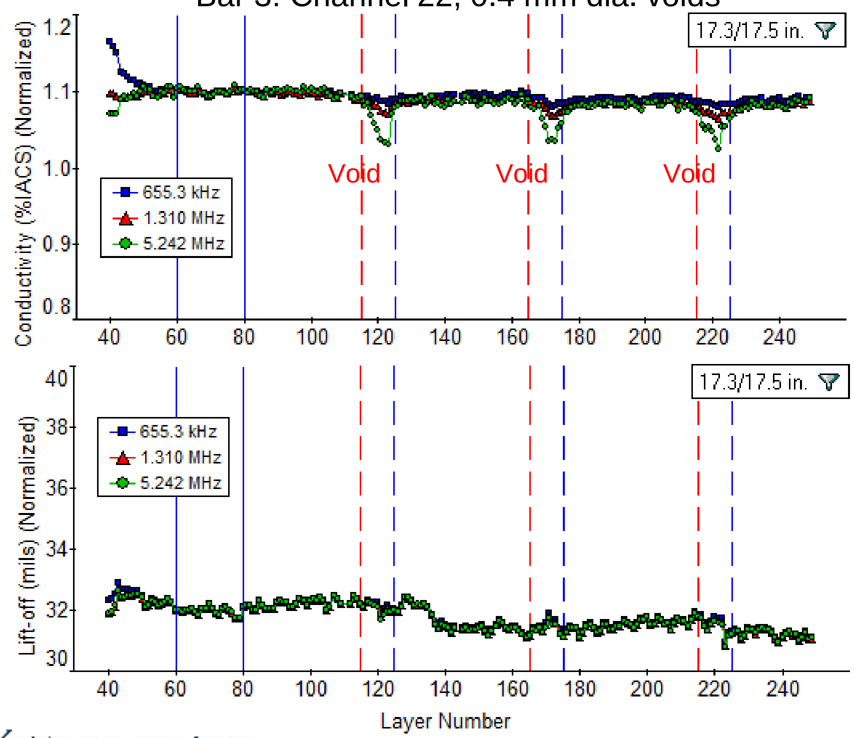
Bar 4: Channel 15



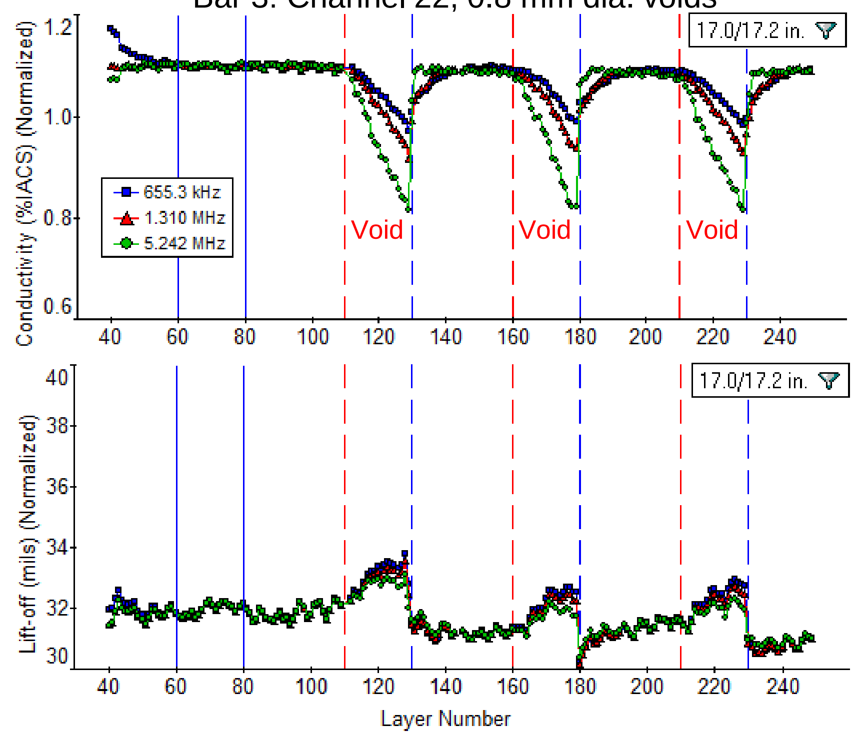
Example 2: B-Scan Responses for Z-direction



Bar 3: Channel 22, 0.4 mm dia. voids



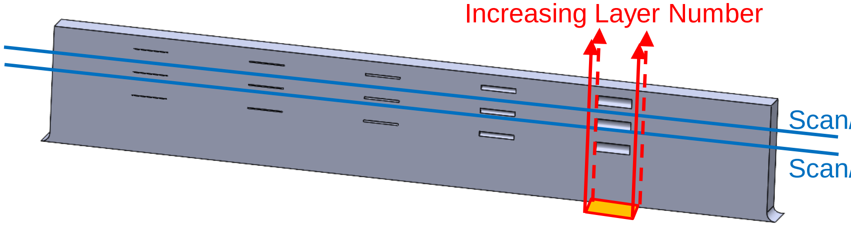
Bar 3: Channel 22, 0.8 mm dia. voids



Example 2: B-Scan Plots (bar 3)

Nominal response over region associated with 0.8 mm dia. void

Region Response for Increasing Layer Number

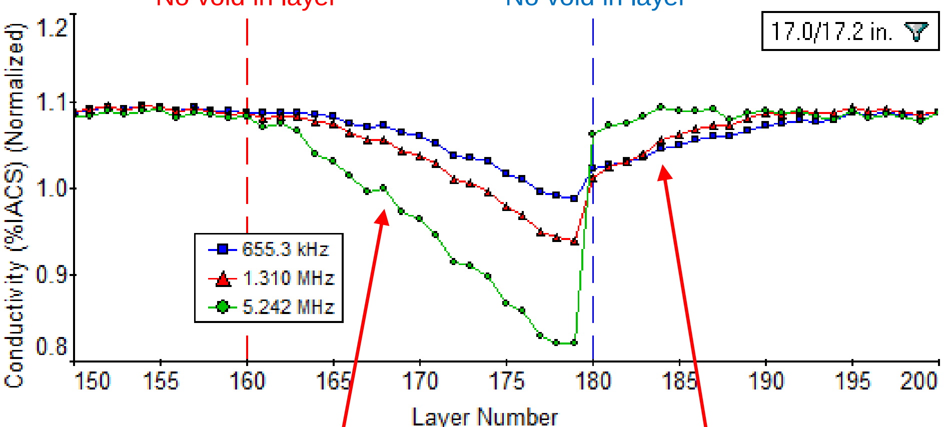


Scan across (x) build region for each layer (typical scan response)

Variation of response in build (z) direction

No void in layer

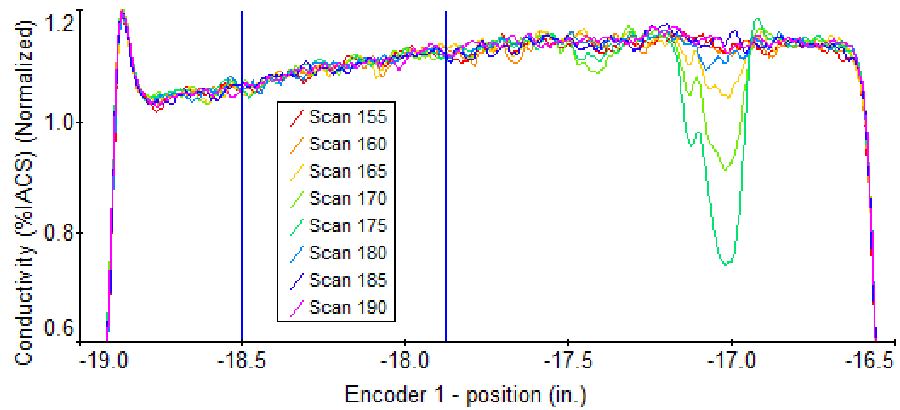
No void in layer



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

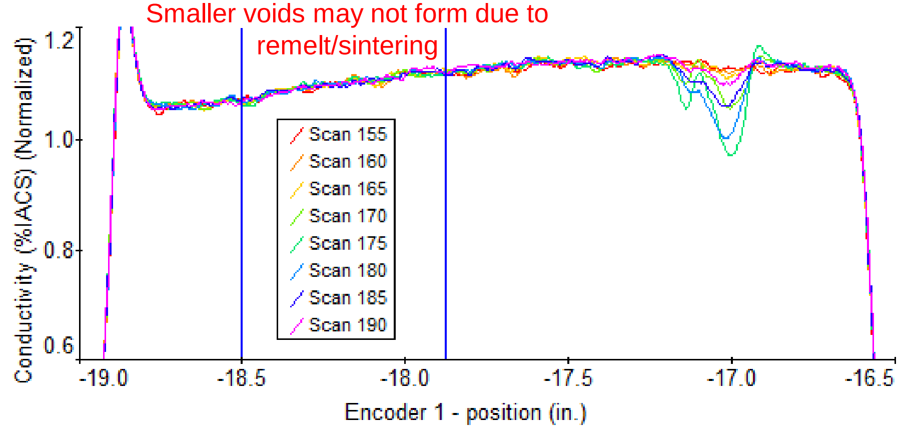
Subsurface void – high frequency shows void covered but lower frequencies see void for more layers

Bar 3: Channel 22, 5.24 MHz

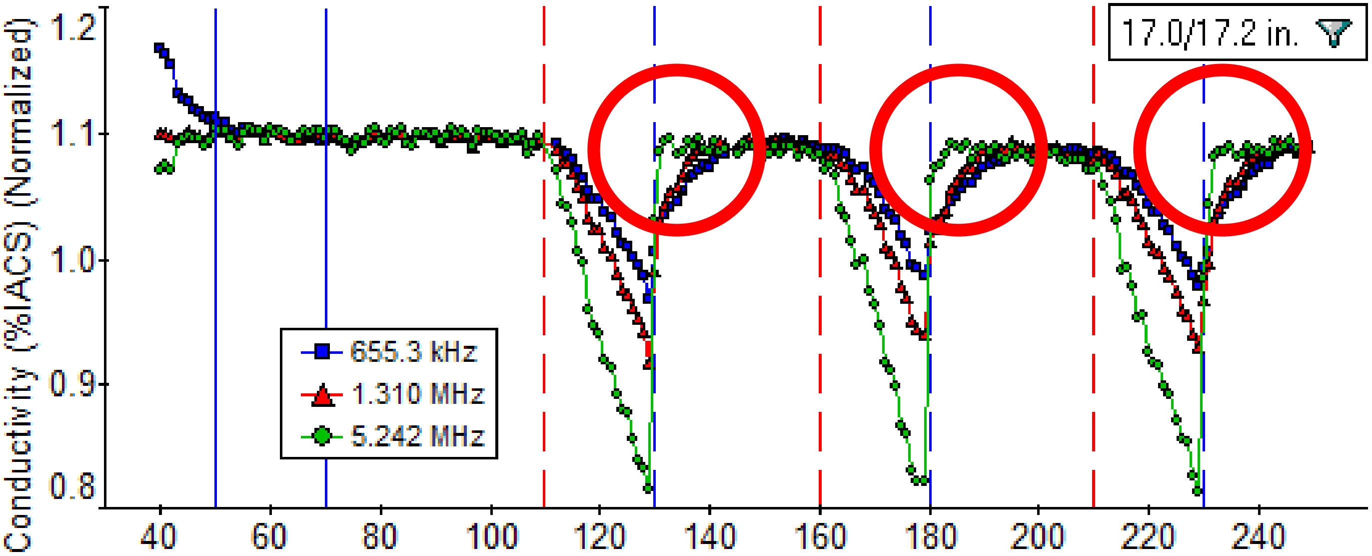


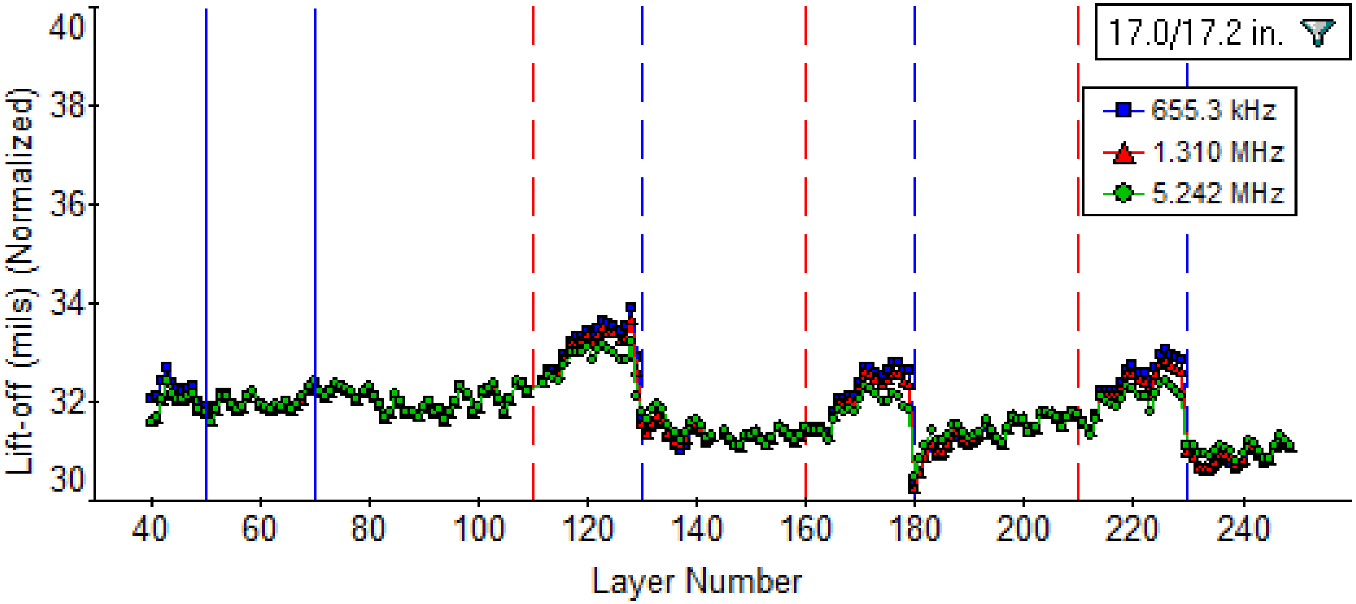
Bar 3: Channel 22, 655 kHz

Smaller voids may not form due to remelt/sintering



Lower Frequencies Detect Void Through More Layers





0.8 mm diameter void metallography

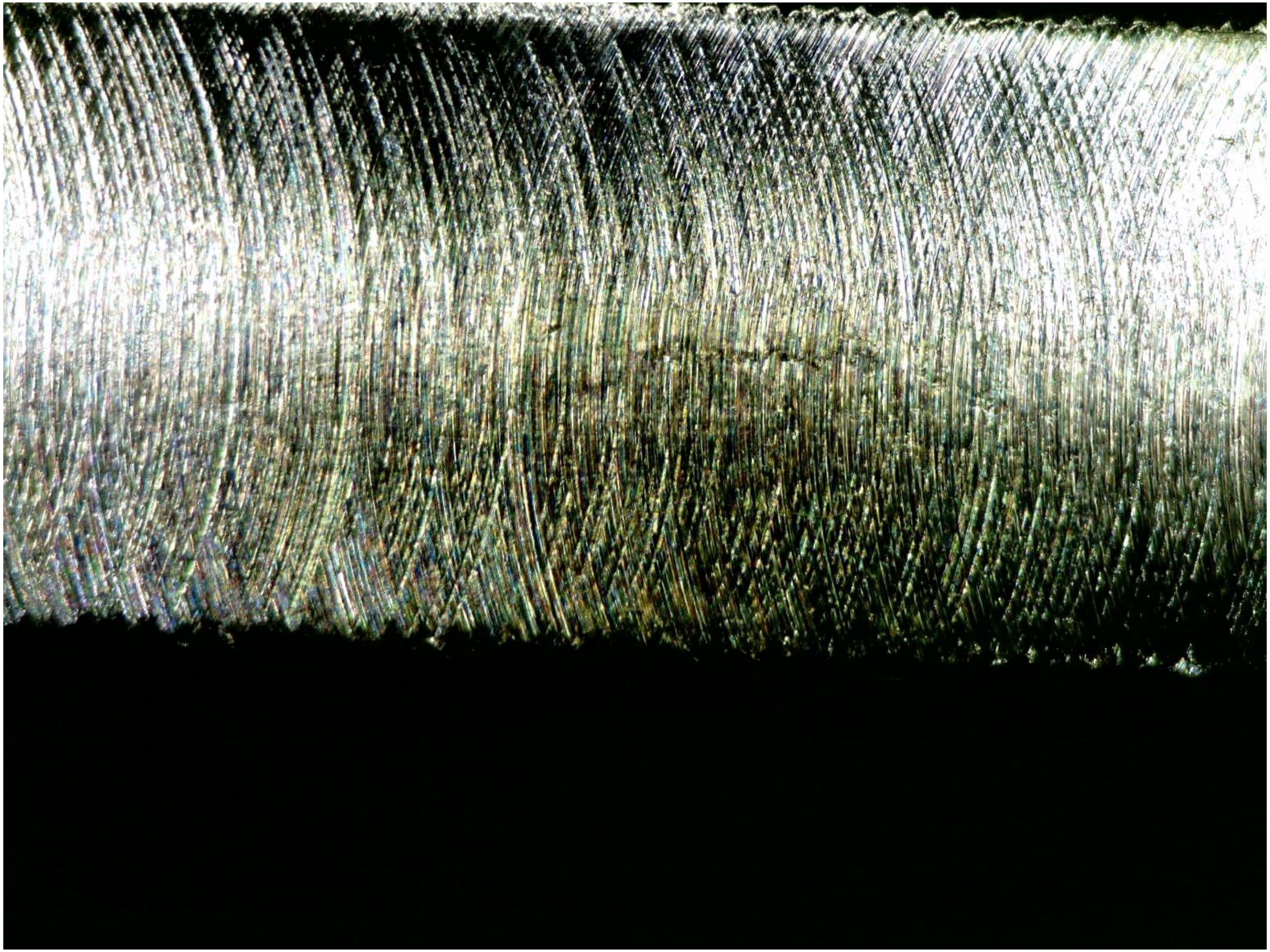
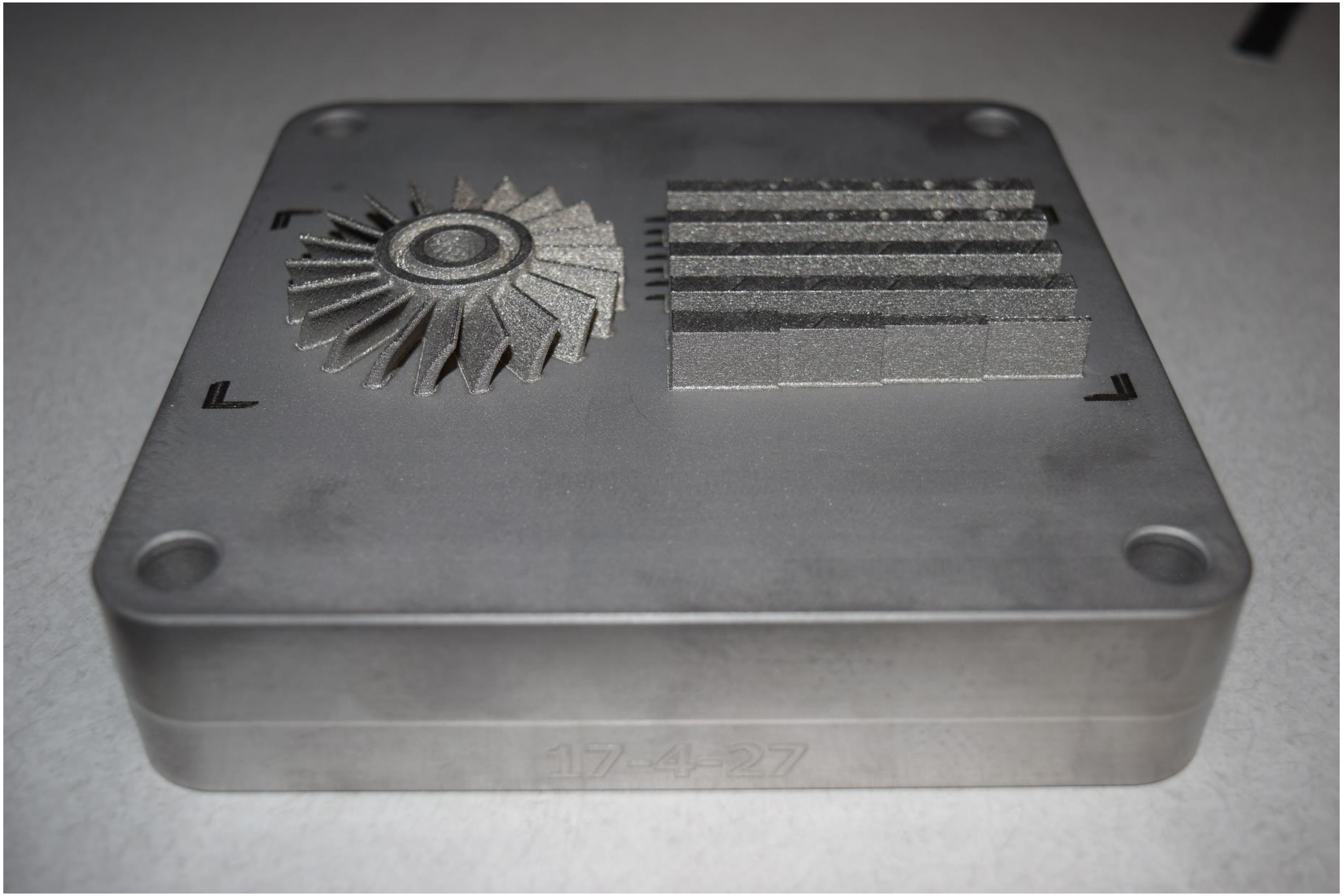


Photo of 249-layer Build (nickel alloy 718)

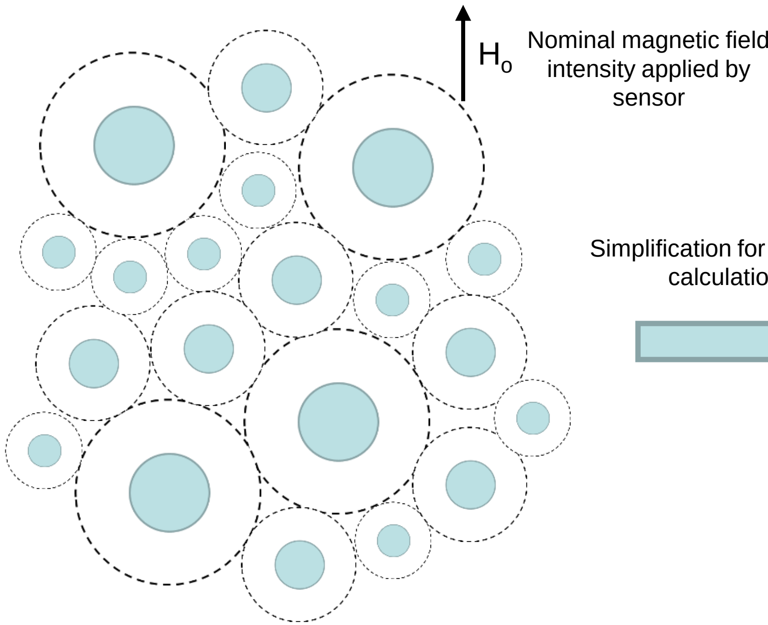


Preliminary Example Rendering of MWM-Array Data

Powder Model (Composite Sphere Assemblage)

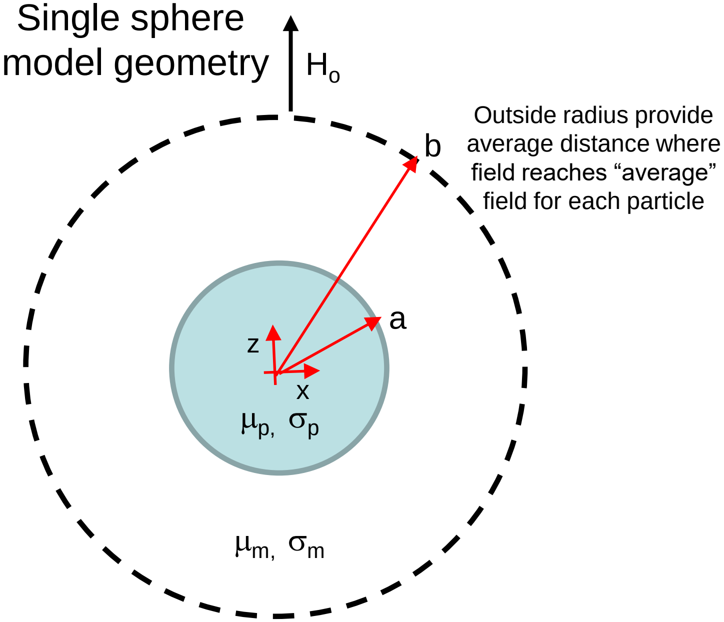
- Unpublished eddy current particle model extension spans low frequency (no eddy currents) to high frequency (thin skin depth compared to particle diameter) regimes

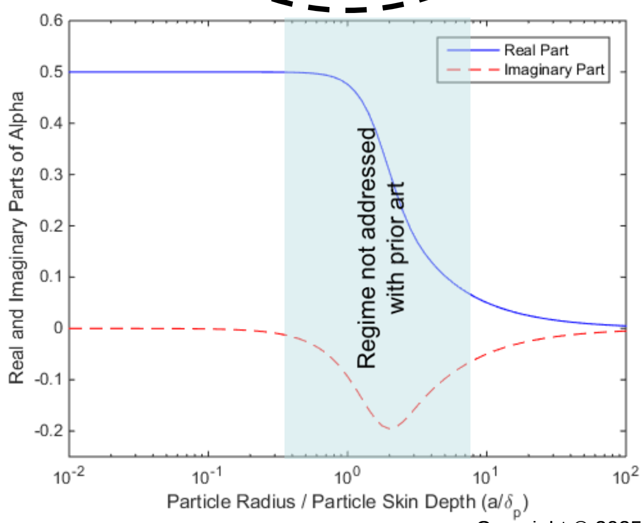
Sphere assemblage



Simplification for local field calculations

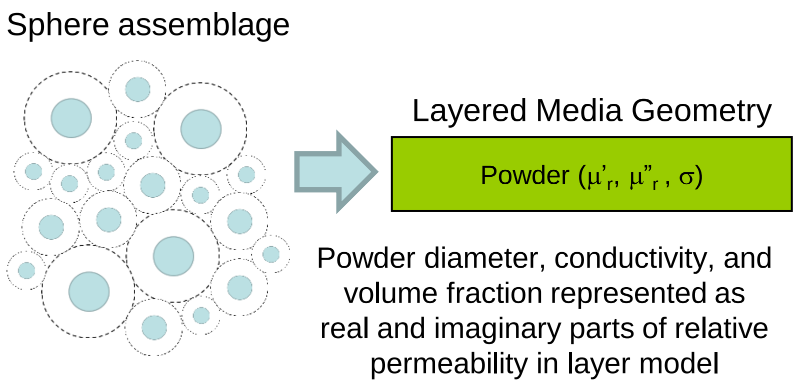
Single sphere model geometry

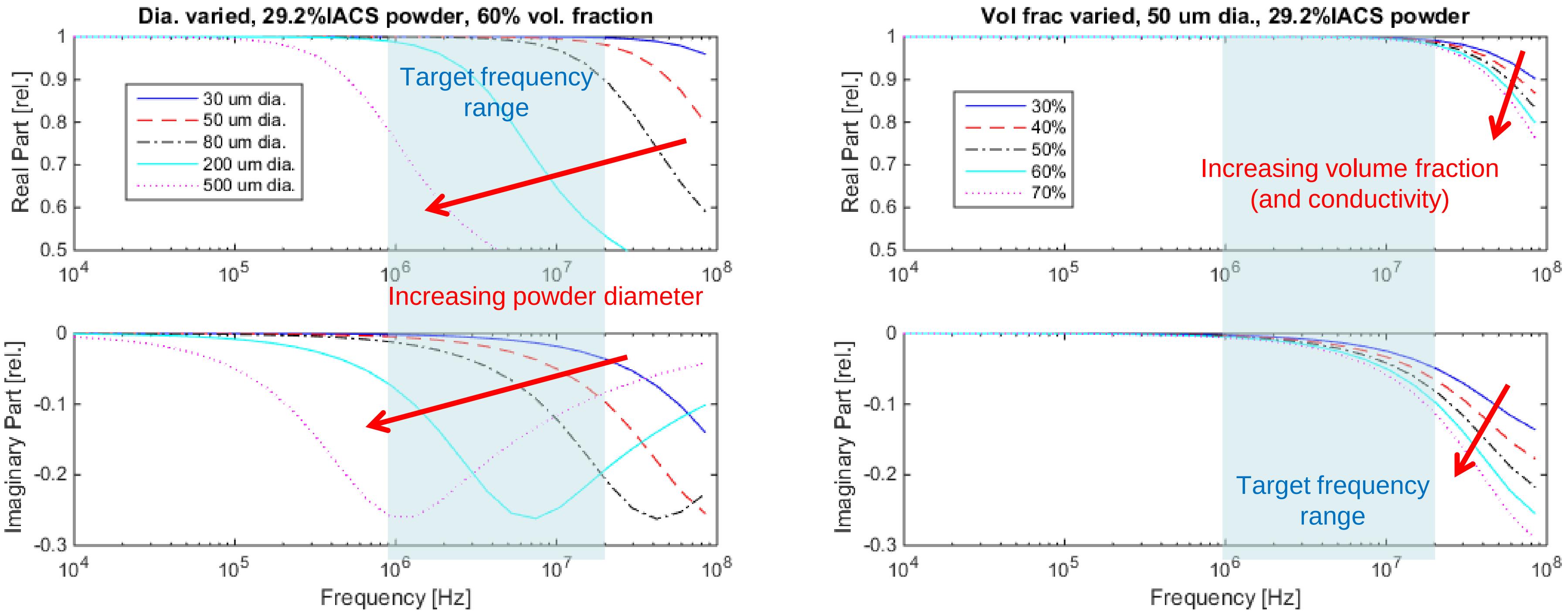




Powder Model – Example Predicted Responses

- 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





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