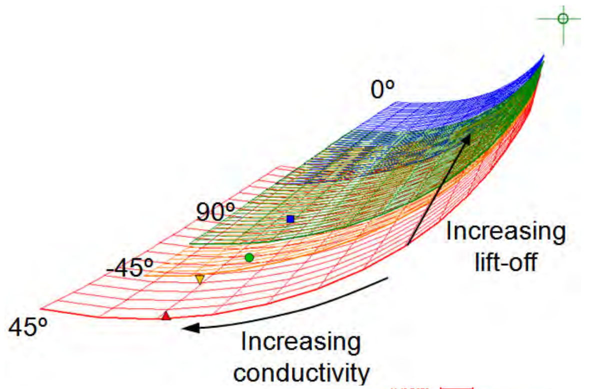
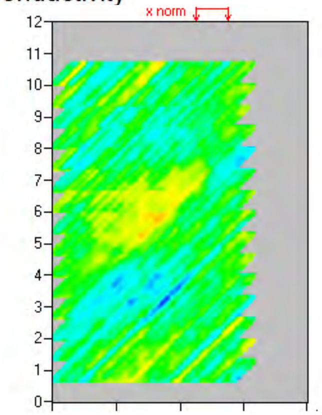
ASNT Spring Research Symposium 2013
Memphis, TN
March 18-21, 2013



Eddy Current Inspection of Composites



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Presentation Outline

- Background
  - Development program goals
  - MWM-Array® technology
  - Depth of penetration of sensing fields
- Basic model predictions and validation measurements
  - Eddy-current extension of micromechanical model
  - Orientation effects
  - Field spatial variations
- Example imaging applications
  - Volumetric imaging of damage
  - Composite Overwrapped Pressure Vessel imaging
- Summary

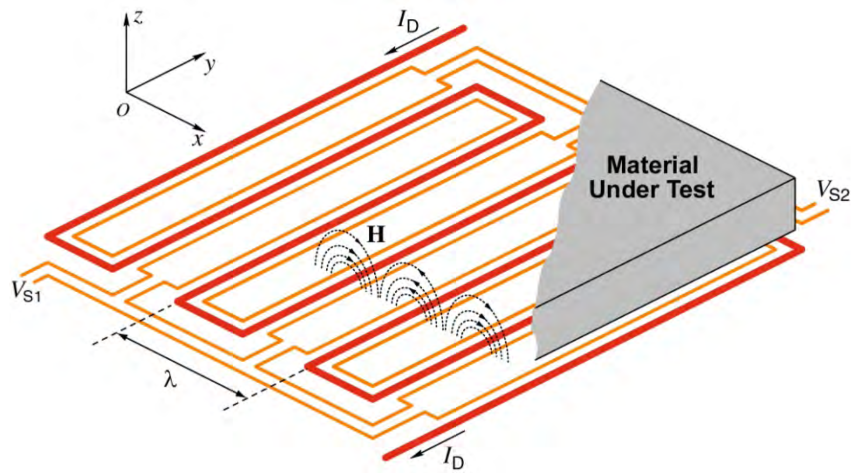
Development Program Approach

- Goals
  - To develop model-based methods for (primarily) carbon fiber composite NDT
  - To demonstrate high resolution damage and condition imaging for composites
  - To develop volumetric stress sensing magnetic stress gages for composites
- Approach
  - Focus on eddy current methods and sensor designs that are readily modeled.
  - MWM-Arrays uses a linear drive eddy current sensor array construct
    - Can induce eddy currents in the linear fibers of carbon fiber composites
    - Use winding geometry changes to alter penetration depth and assess material condition (e.g., damage and stress)
- Funding
  - NASA for micromechanical model development and application to composite overwrapped pressure vessels (COPVs)
  - Army for rotorblade NDT
  - Navy for NDT of aircraft composites

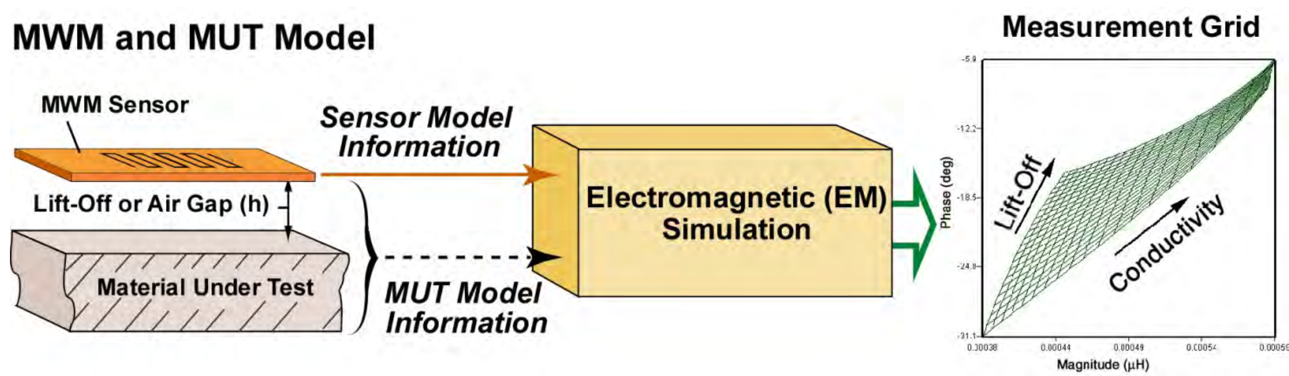
MWM®-Array Technology

- Eddy current array geometry designed to match (isotropic) models for responses
- The voltage induced on sense element(s) is measured.
- Measurement grid methods provide conversion of measured responses into physical properties (e.g., conductivity, lift-off, permeability)

Magnetic field interacting with test material



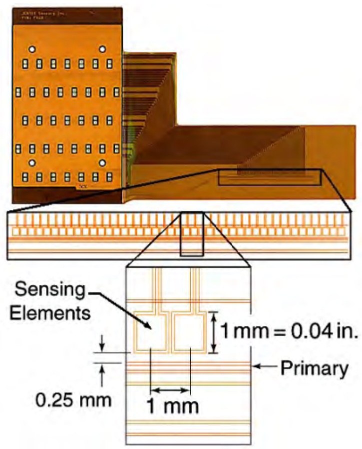
Measurement Grid Methods



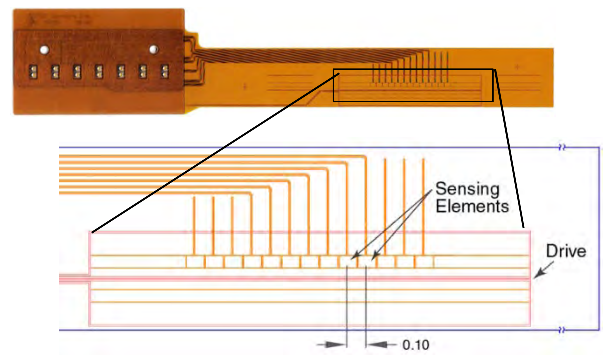
Example MWM®-Arrays

- MWM-Array dimensions can be adjusted for the application
  => Drive-sense gap (spatial wavelength) affects penetration depth

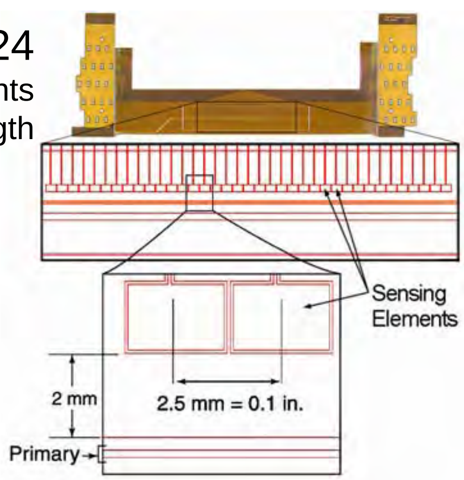
FA28
37 elements
small wavelength



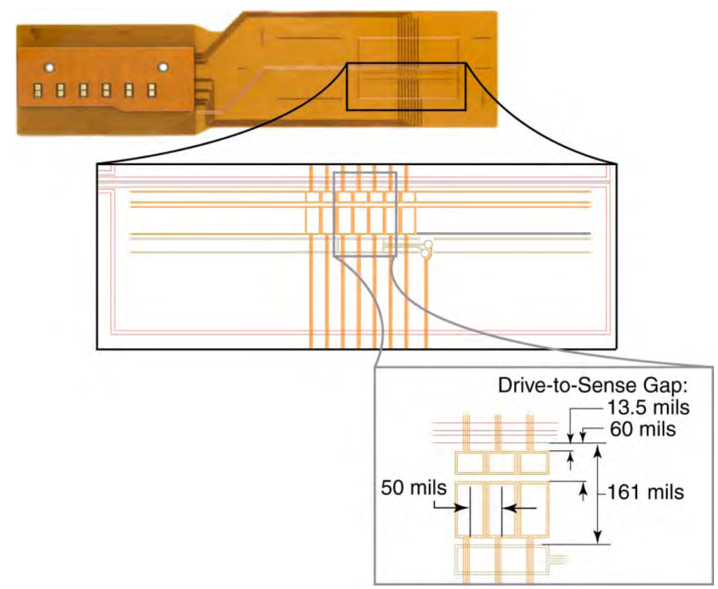
FA154
7 elements
medium wavelength



FA24
37 elements
large wavelength

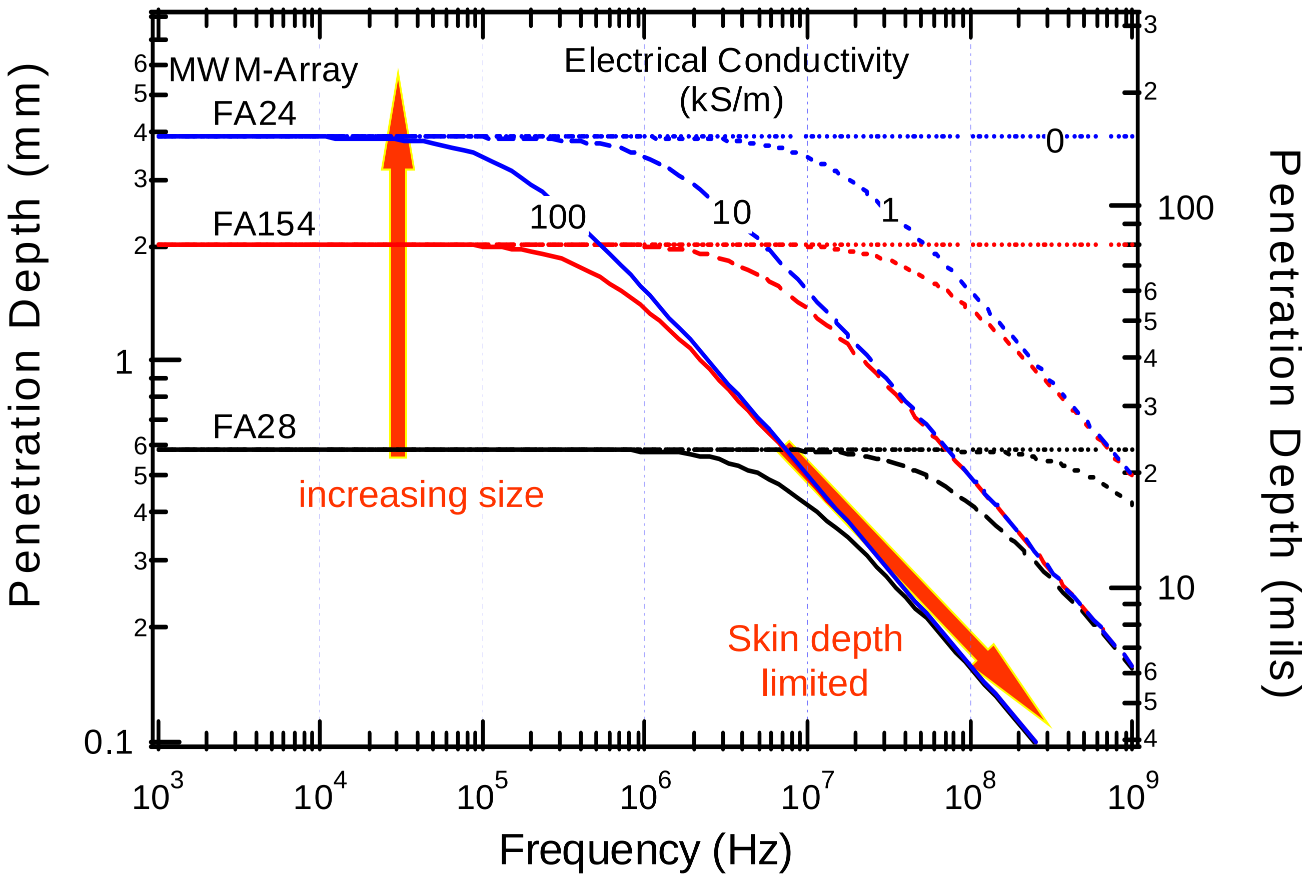


FA49
7 elements
several wavelengths



MWM-Array Depth of Penetration

- Magnetic field decays exponentially with distance away from sensor
  - Decay rate determined by skin depth at high frequencies and sensor dimensions at low frequency



Spatial Fourier Mode Depth of Penetration = $1/\mathrm{Re}(\Gamma_n)$

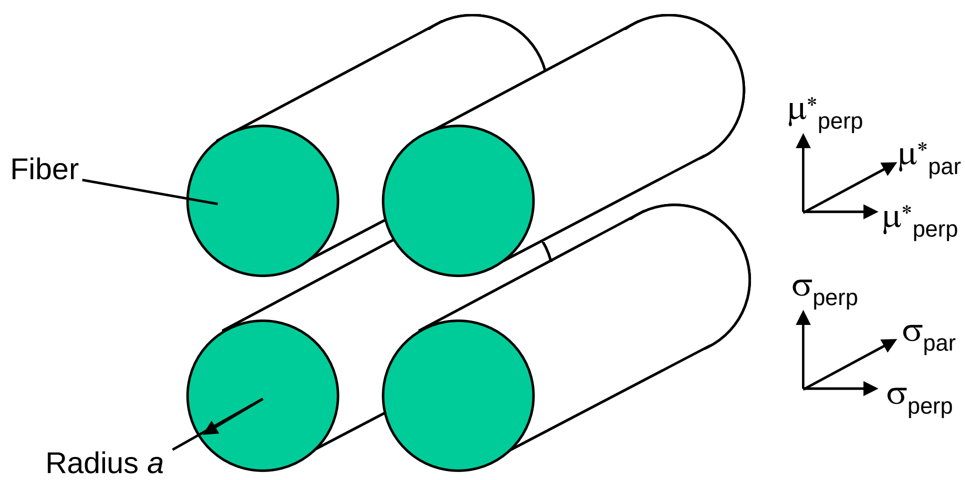
$$\Gamma_n = \sqrt{(2\pi n/\lambda)^2 + j2/\delta^2}$$

Skin depth: $\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$

Micromechanical Model: Eddy-Current Extension

- Model considers fiber bundles as a composite cylinder assemblage
  - Solve for field around a single fiber and extend to fiber bundle
  - Effective complex permeability and conductivity depend upon orientation with respect to fiber axis, fiber density and fiber contact
- For carbon fiber composites
  - Graphite fibers: ~7 μm diameter, nonmagnetic, ~20 kS/m (0.0344%IACS)
  - Radius << skin depth for typical eddy-current frequencies
- Indicates a strong orientation dependence of the properties
  - MWM-Arrays with linear drives can provide a measure of these orientation dependent responses

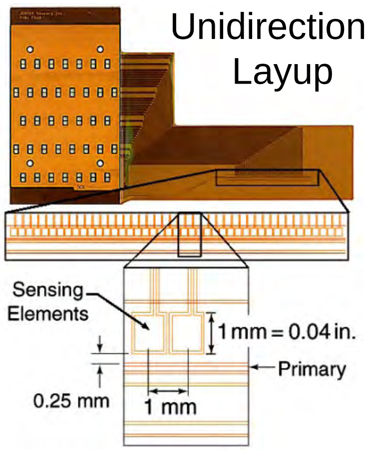
$\mu^*_{par} \approx \mu^*_{perp} \approx \mu_o$ $\sigma_{perp} \approx 0$ $\sigma_{par} \approx \sigma_f \nu_f$



This first order model neglects interconnections (touching) between fibers

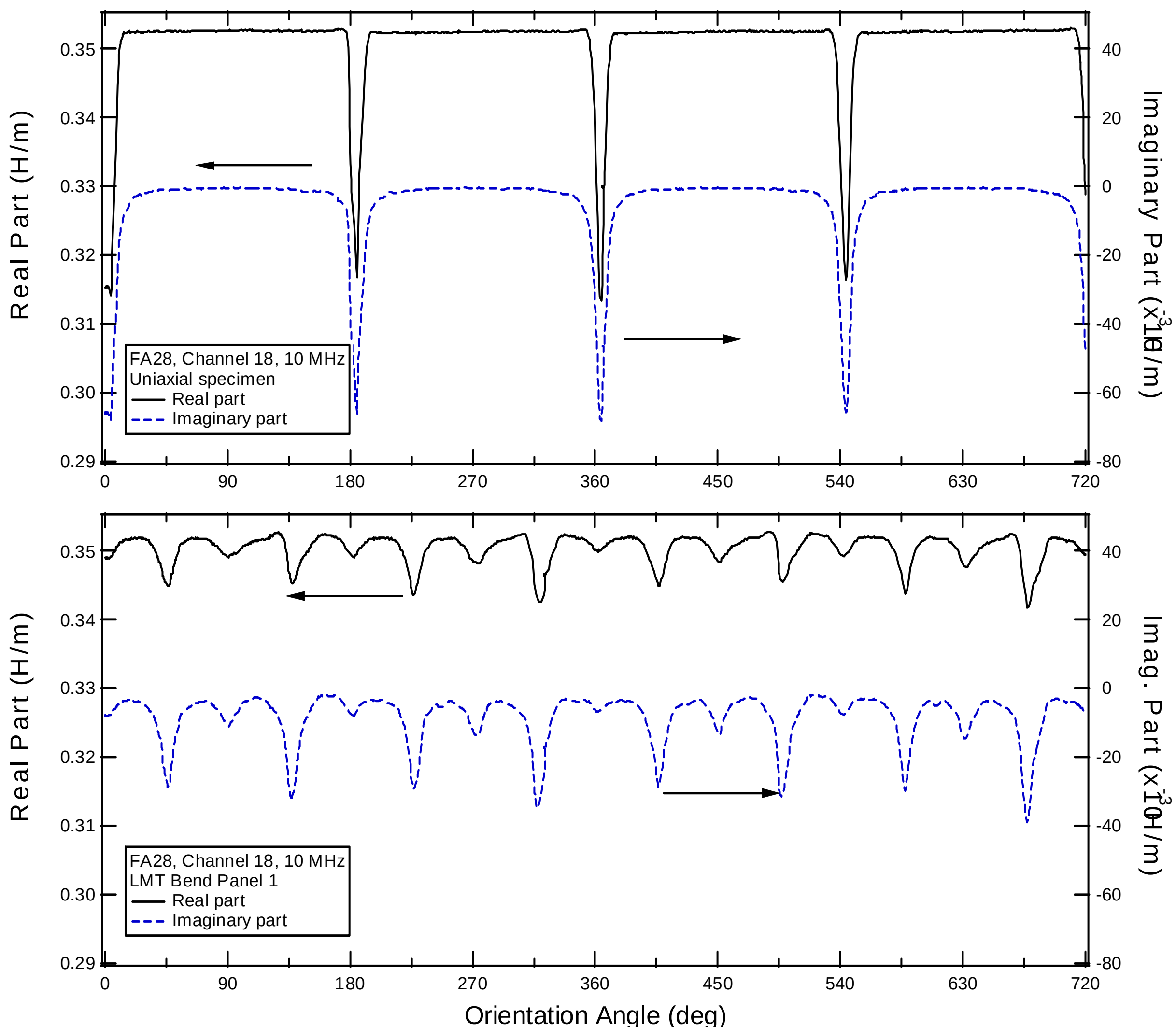
Composite Measurements: Orientation Effect

- Center element for FA28 MWM-Array
- Strong response when aligned with fibers in individual plies



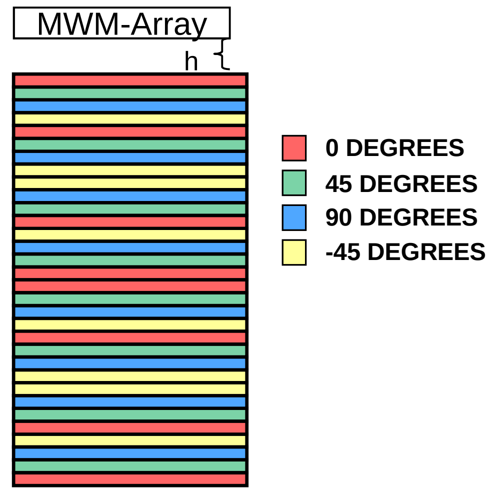
Unidirectional Layup

Quasi-isotropic Layup (alternating layers at -45º, 0º, 45º, 90º)

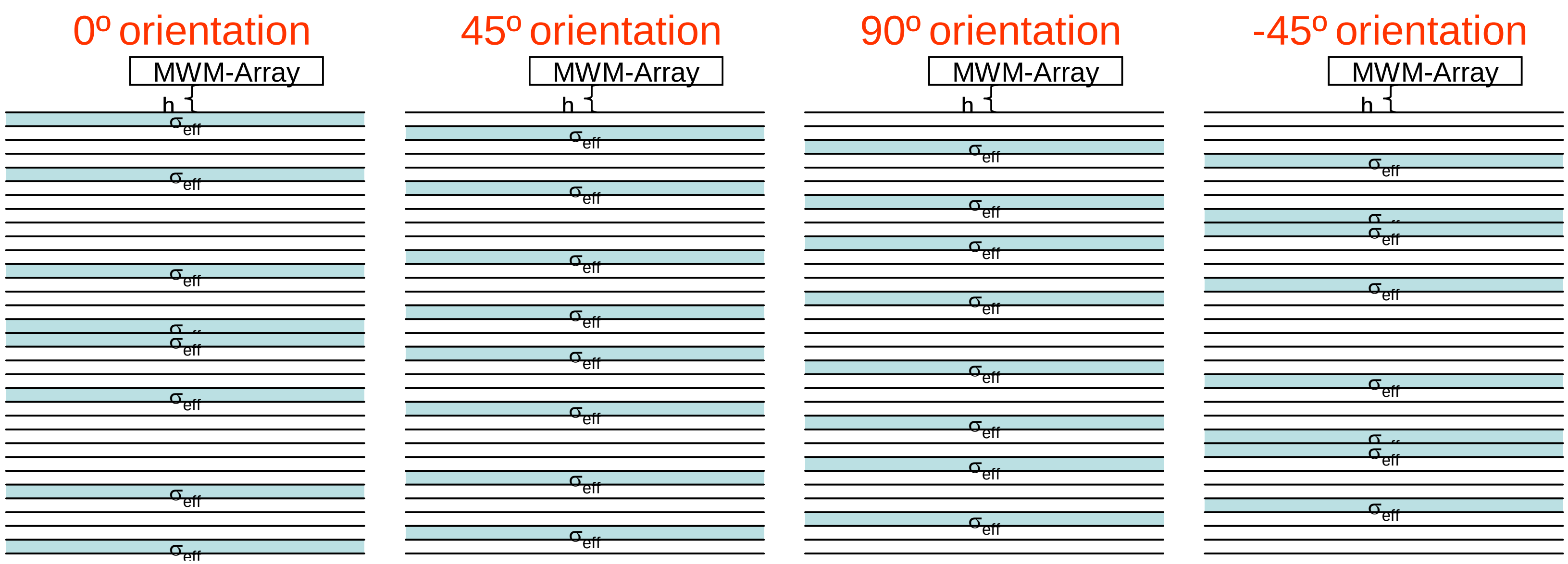


Simple layered-Media Composite Representation

- Layup for quasi-isotropic test panel
  - Uniaxial properties for each layer
- MWM-Array sensitive to composite layers with fibers oriented parallel to drive windings
- Composite layer considered insulating if fibers NOT within several degrees
- This visualization indicates that each sensor orientation is only sensitive to a subset of plies at varying depths within the composite.

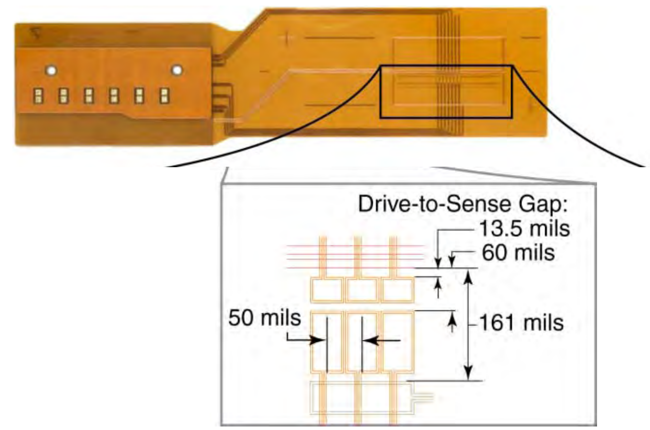


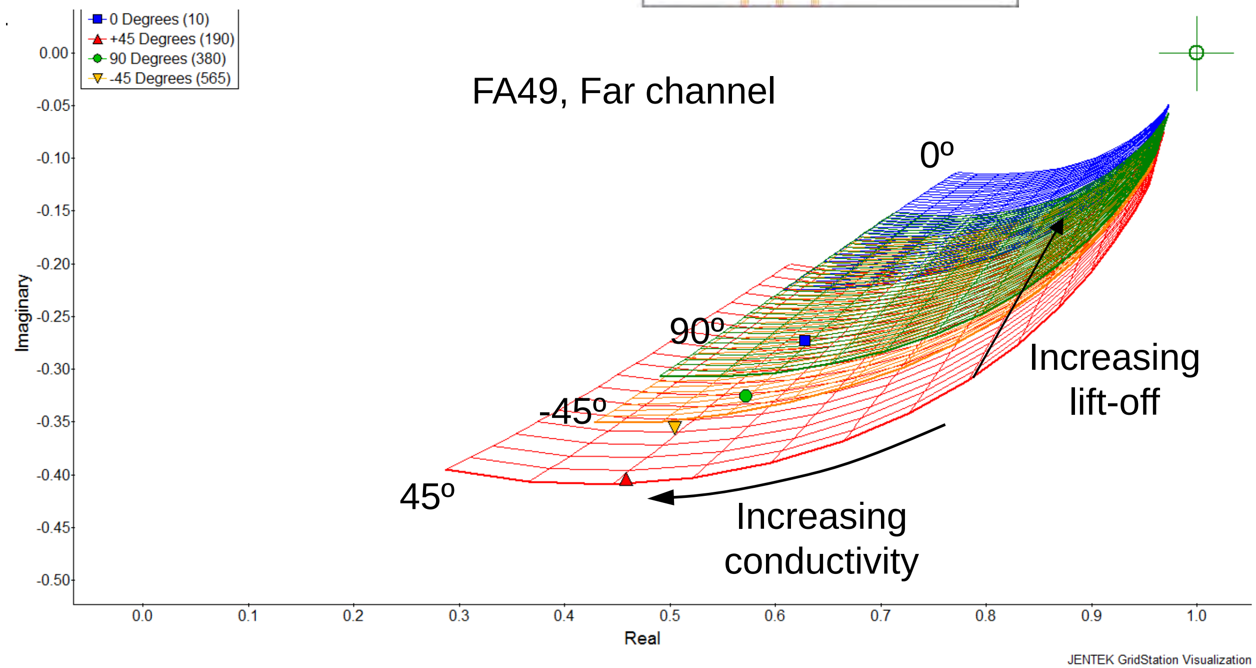
(note that the angle is relative to the fibers at the surface)



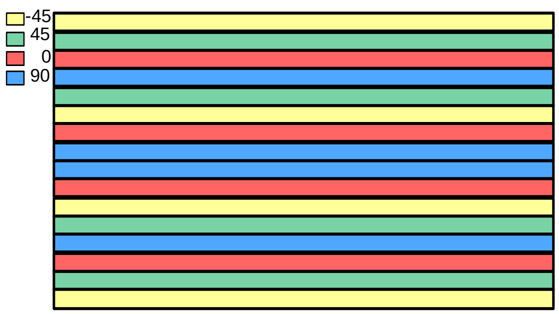
Layered-Media Composite Grid Example

- Conductivity/lift-off measurement grids assuming quasi-isotropic layup
  - Non-zero conductivity only for aligned layers in each orientation
- Primarily observe response shift as effective lift-off changes with orientation
- General agreement with measurement data in each orientation
  - Data is below the grids for … and 90º), so other factors need to be considered



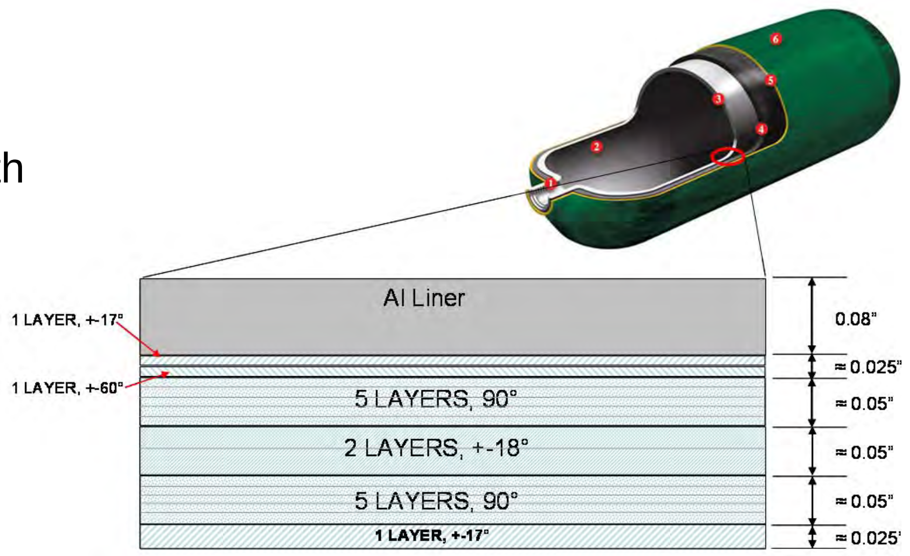


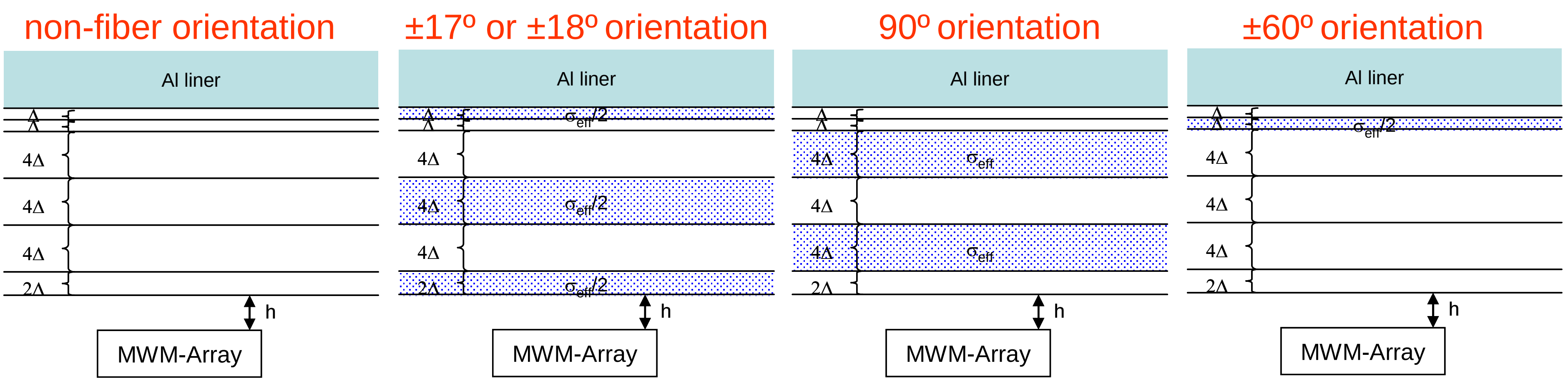
Quasi-isotropic Layup
(note that the angle here refers to the panel orientation)



Example COPV Layup

- Representative layup for Composite Overwrapped Pressure Vessels (COPV)
- MWM-Array sensitive to composite layers with fibers oriented parallel to drive windings
- This indicates that the sensor orientation is important for assessing the fiber properties



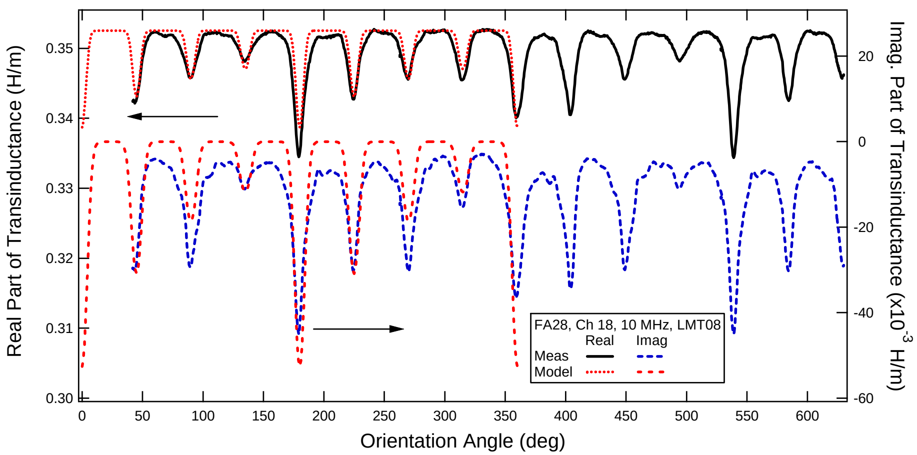


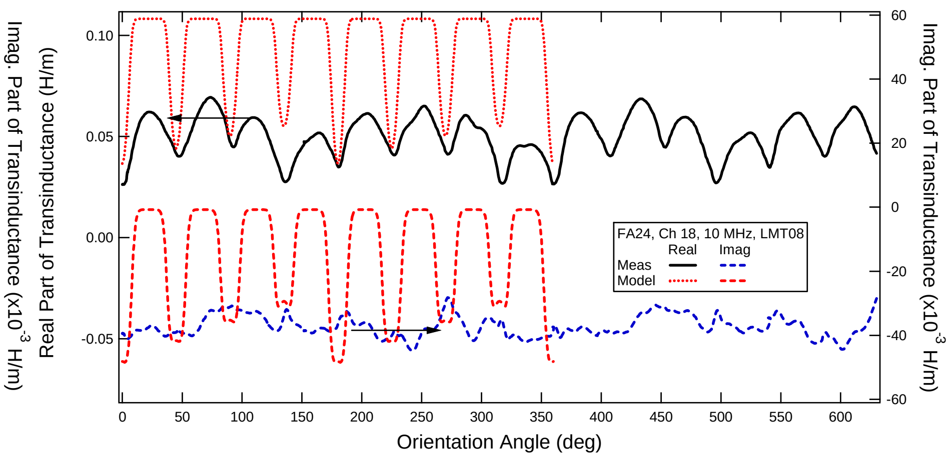
Simpl Layered-Media Model with Measurements

- Gaussian distribution model assumed for fiber conductivity in each layer
- FA28 shows reasonable agreement with rotation measurements
- FA24 shows broader response and background variation consistent with low-level background conductivity (i.e., fiber touching should be considered)

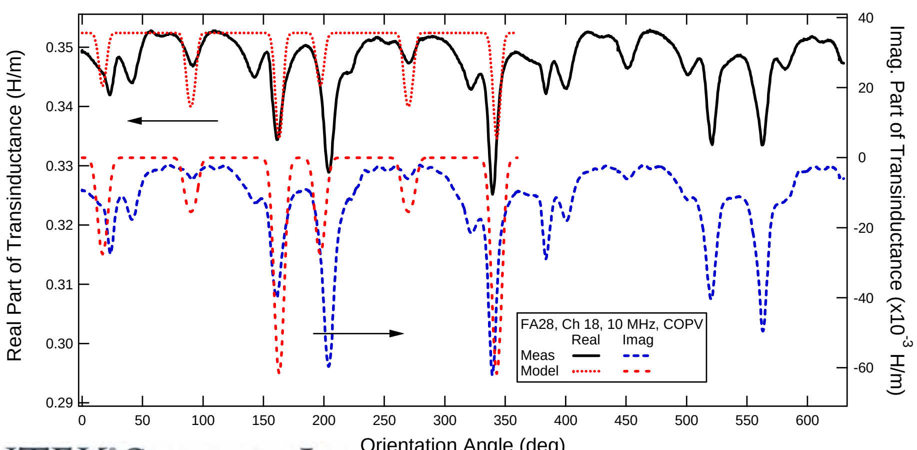
FA28 FA24

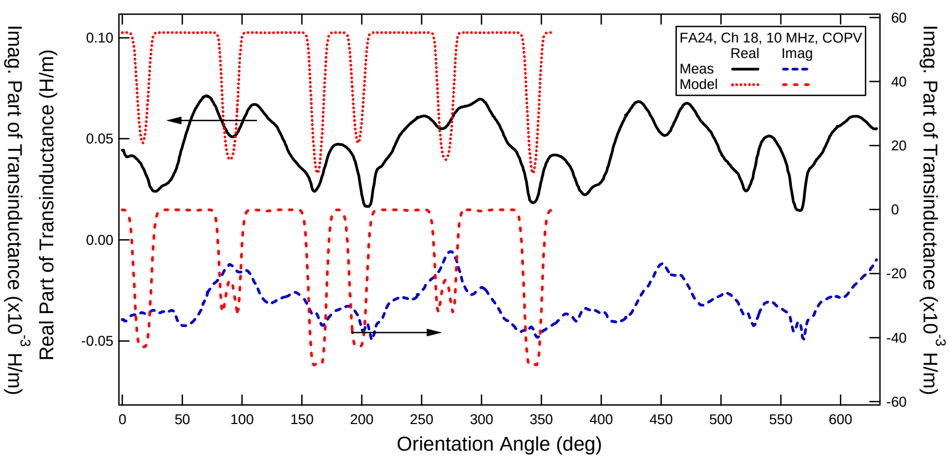
Quasi-isotropic





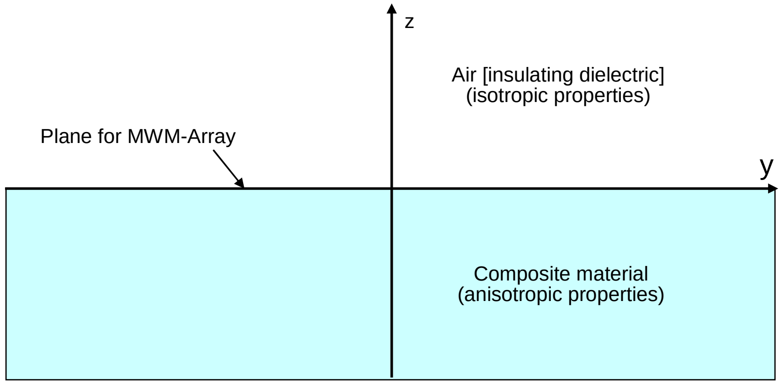
COPV

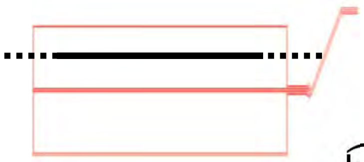




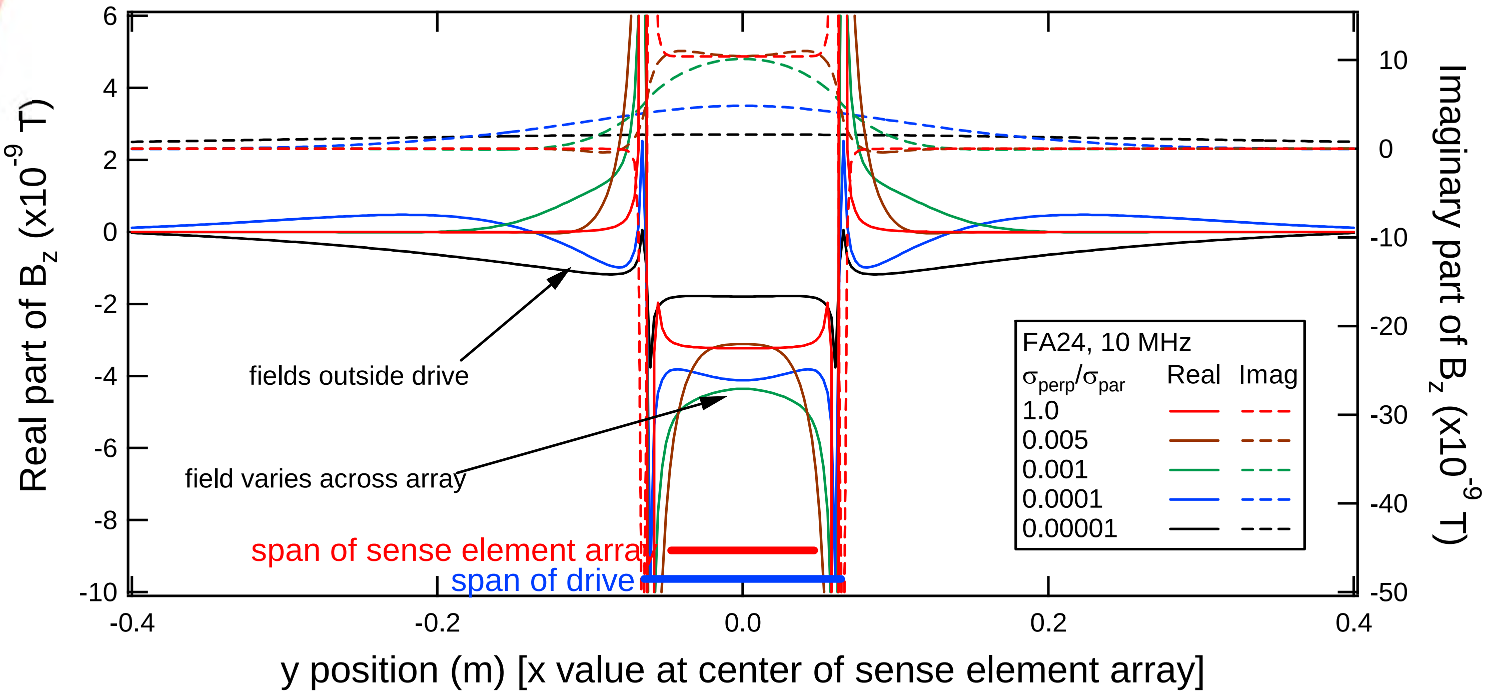
Model Response: Field Variations for Composite

- 3D model for field distribution around drive
- Plots show normal field component along nominal position of sense elements in rectangular loops
  - Drive winding aligned with uniaxial composite fibers
- Field varies with position along sense element array and degree of anisotropy



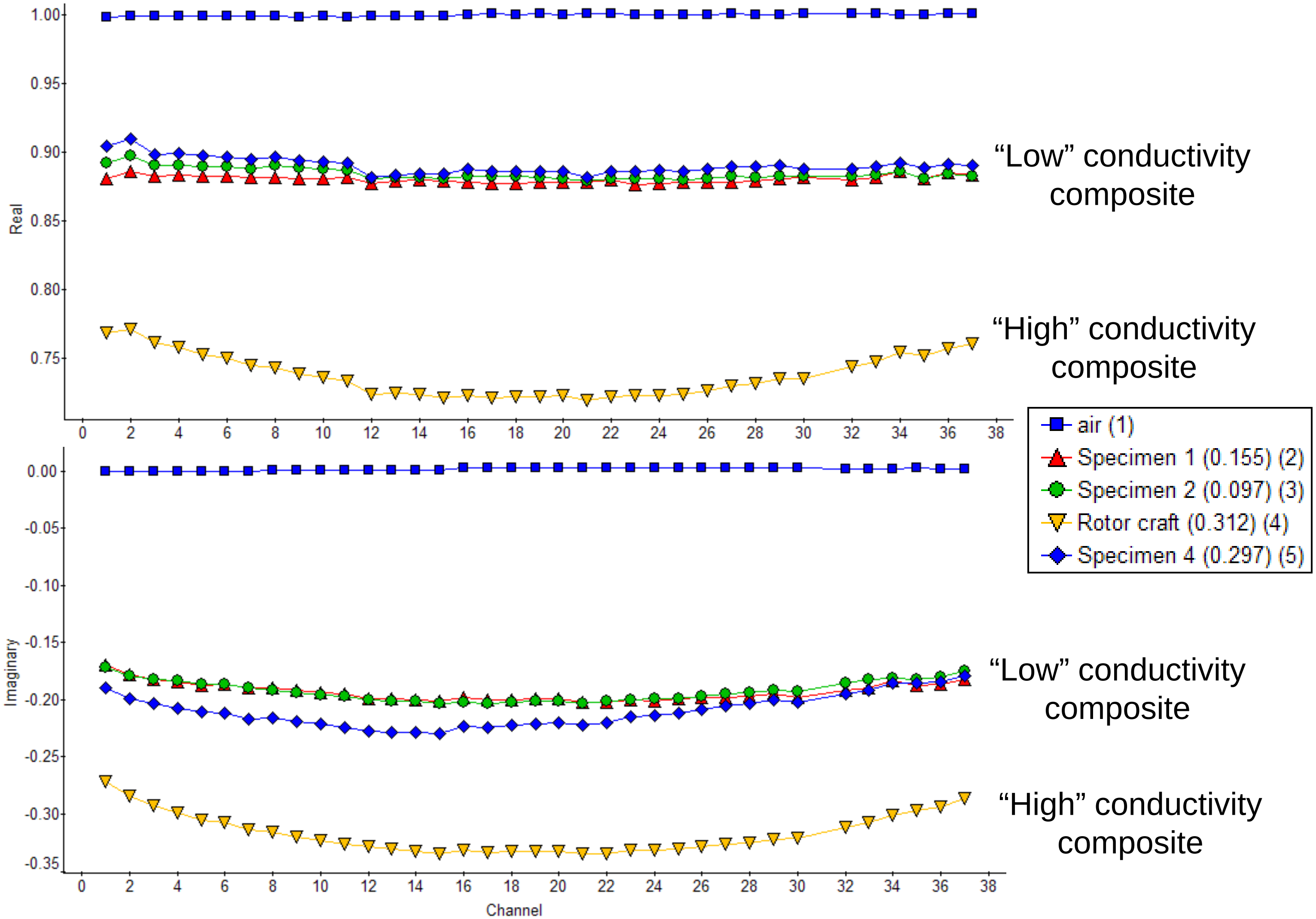


Double-D
Drive Winding



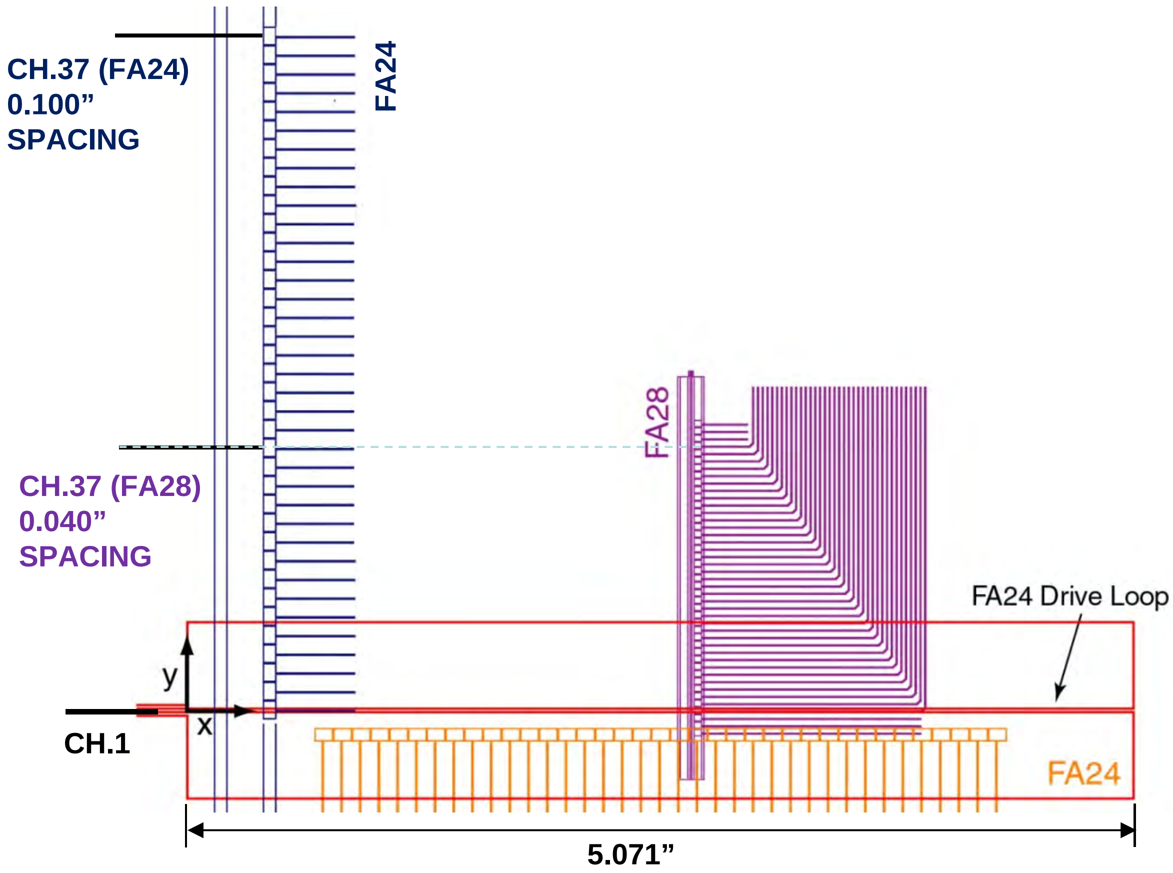
Uniaxial Specimens: FA28 parallel to fibers

- Channel-to-channel variation consistent with field variation along drive winding



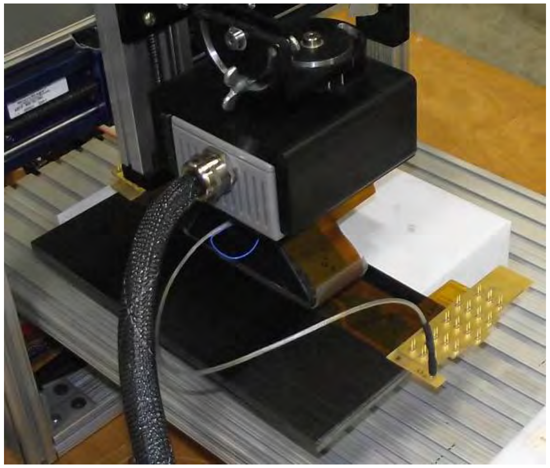
Field Mapping Setup

- Excite drive of a FA24 and scan with sense elements from a second array
- Sense element responses proportional to normal component of field
  - The calibration led to the responses having a negative polarity compared to the previous results



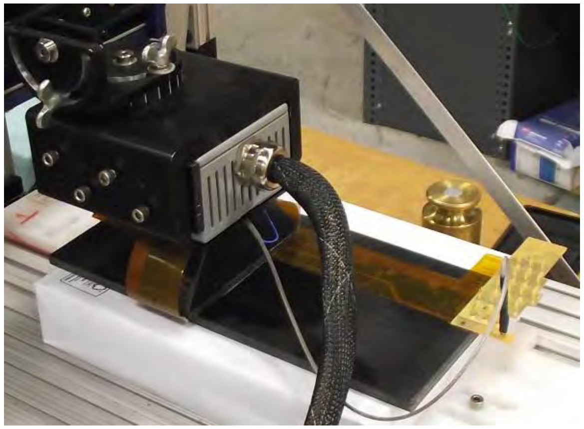
Calibration

(sense elements parallel to drive)



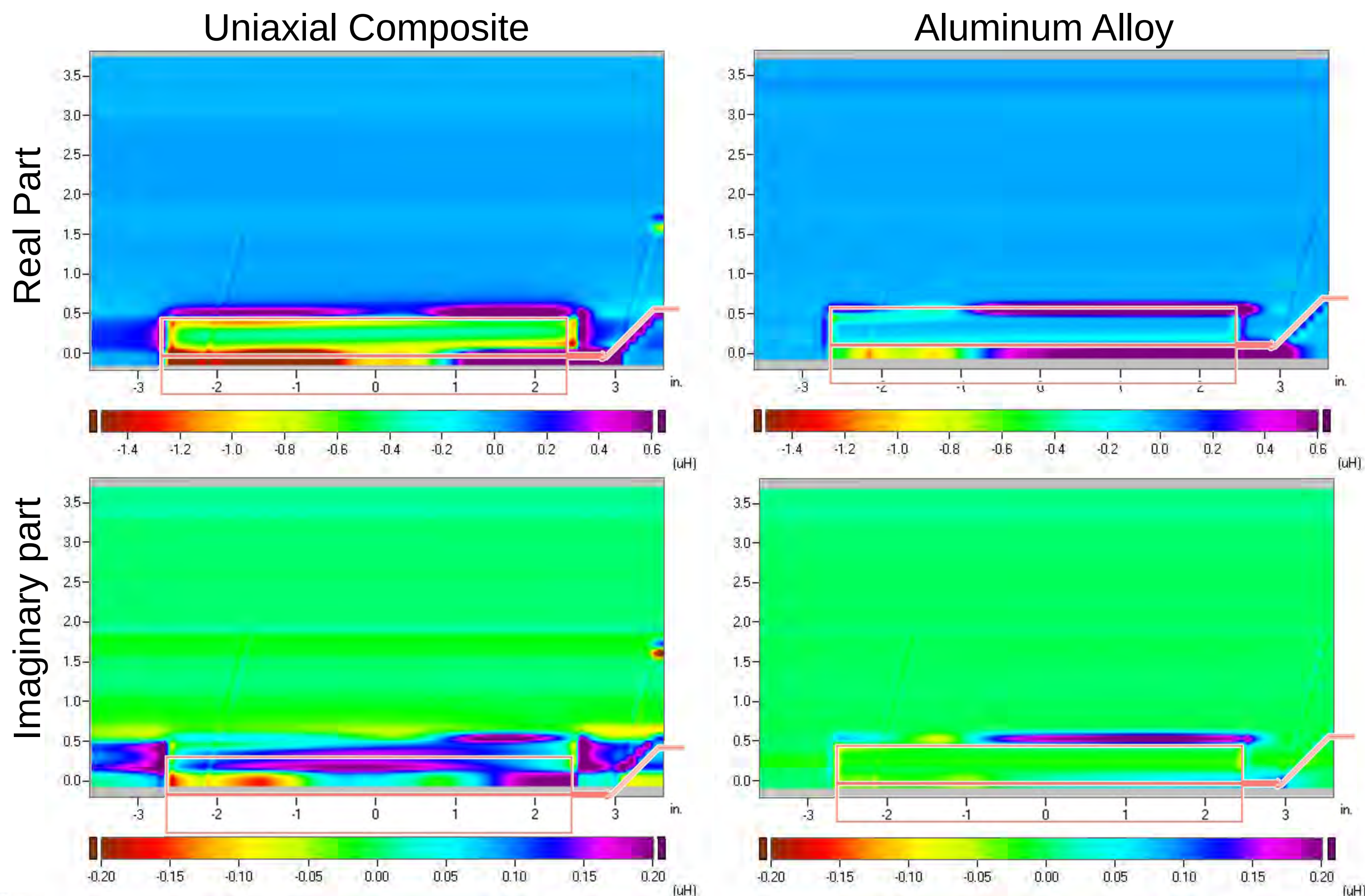
Scanning

(sense elements perpendicular to drive)



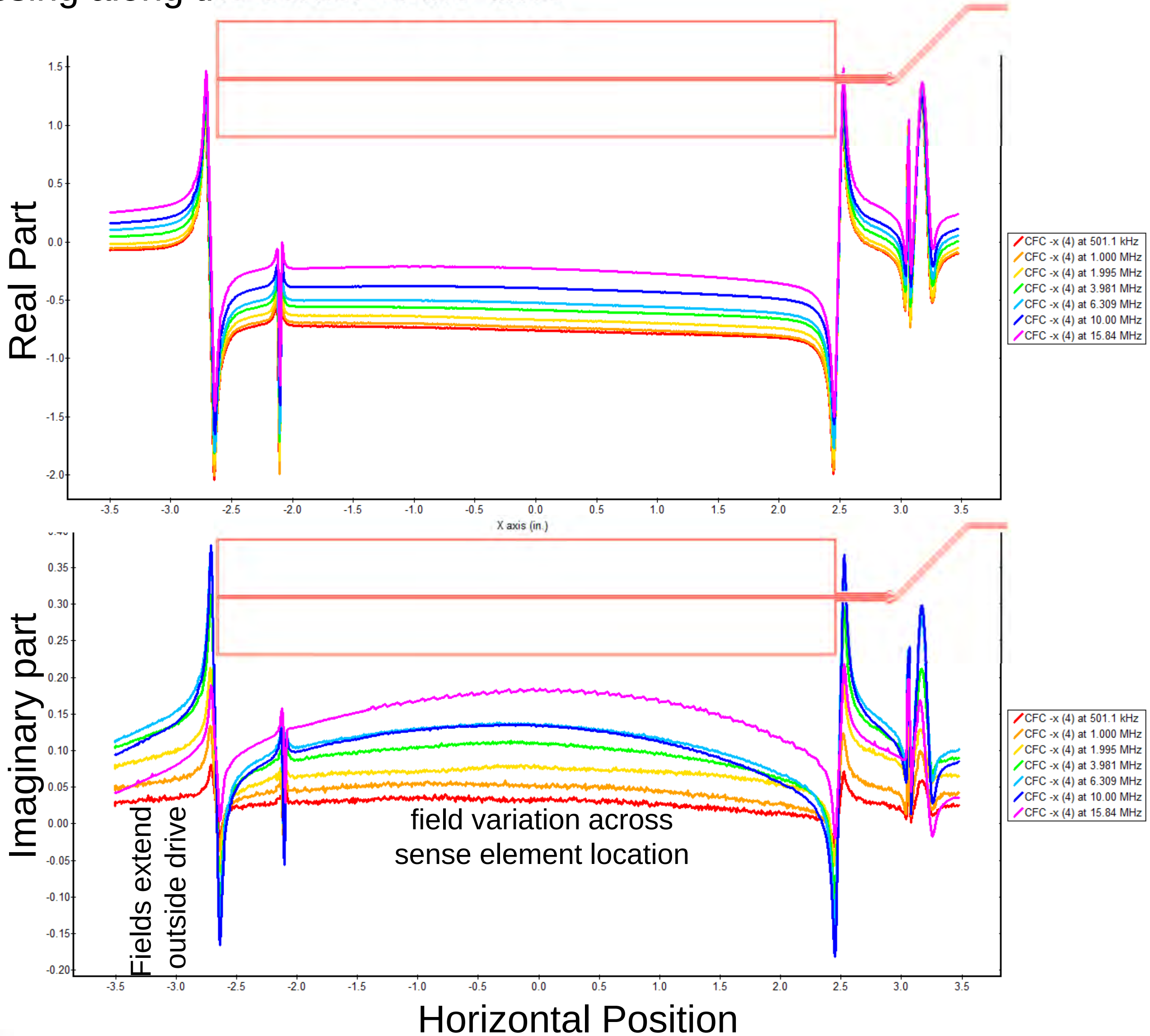
Field Mapping: C-Scans

- Greater field variation for carbon fiber composite
  - Significant field extending beyond the drive winding in the horizontal direction
  - Within the drive, the imaginary part goes though a maximum near the center



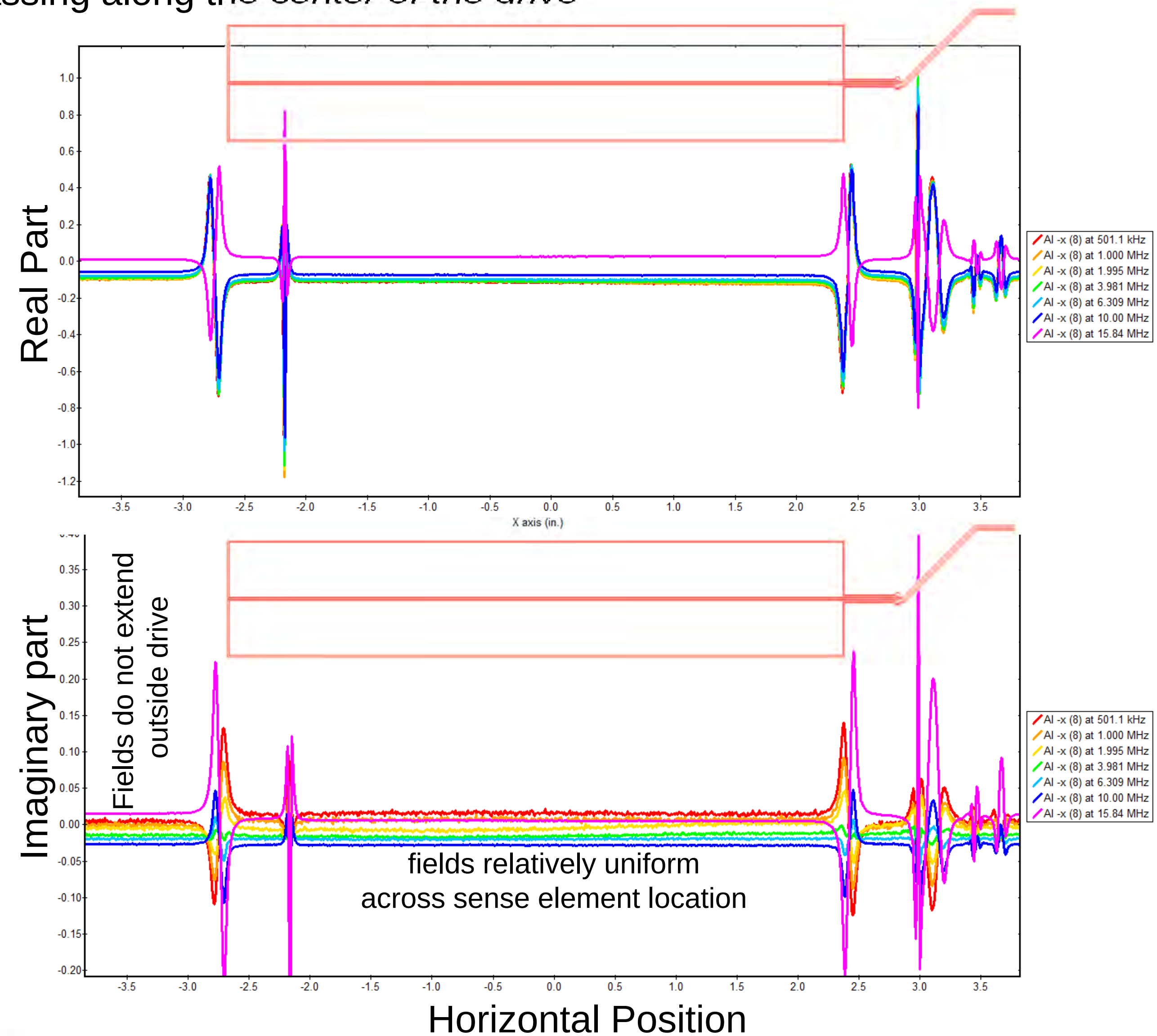
Field Mapping: B-scan, composite

- One channel passing along the center of the drive



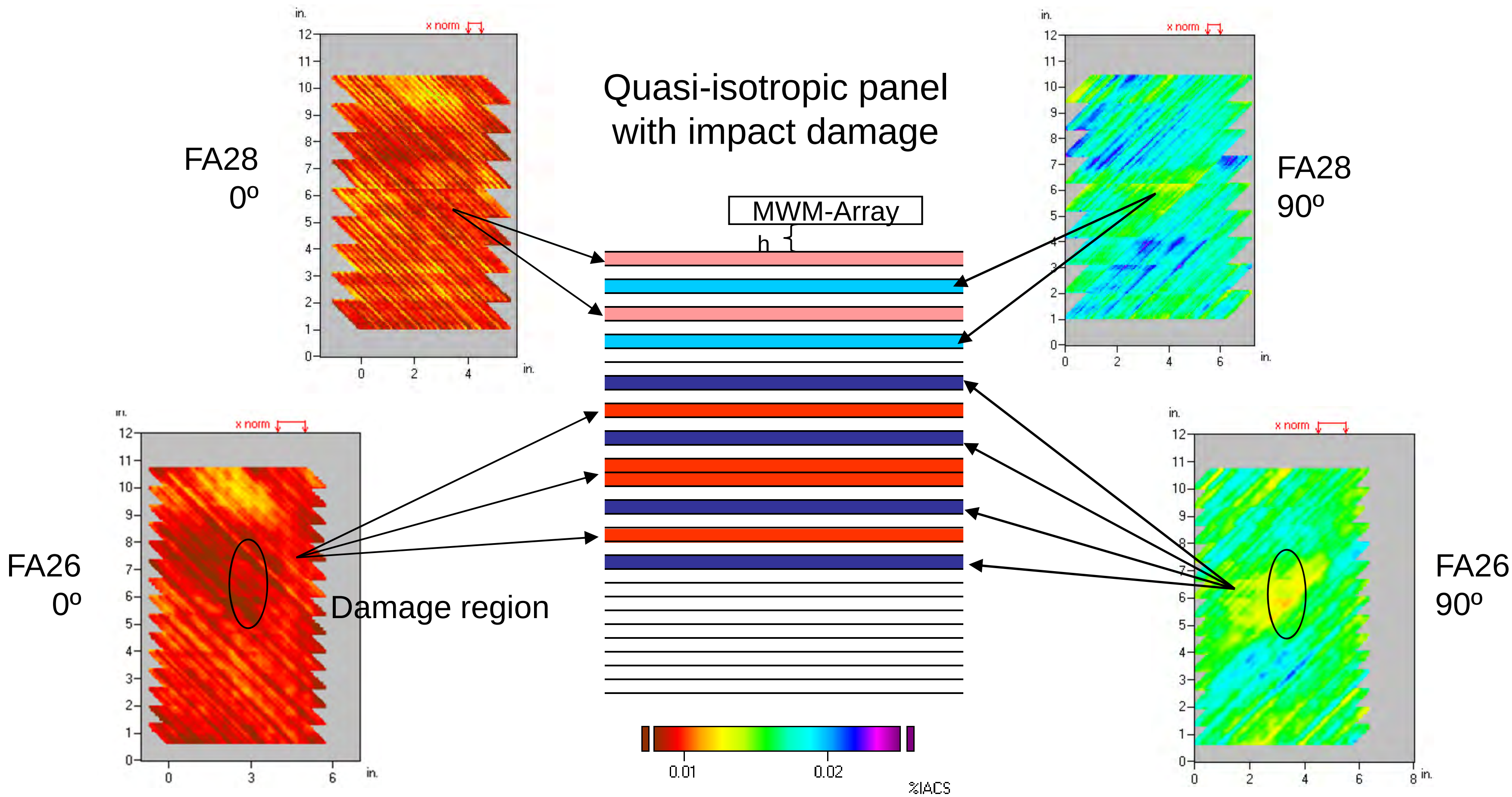
Field Mapping: B-scan, aluminum alloy

- One channel passing along the center of the drive



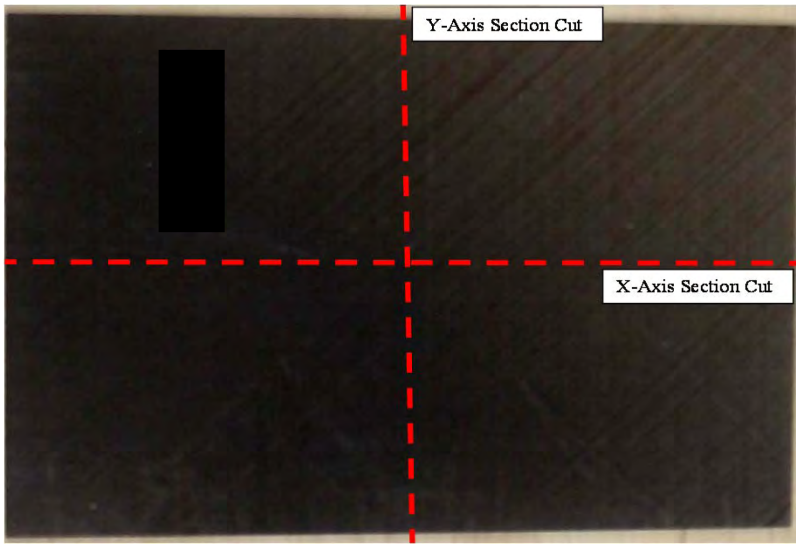
Volumetric Property Imaging Approach

- Combination of sensor orientation and geometry can isolate depth and region of damage
  - sensor orientation determines plies
  - sensor geometry determines depth of sensitivity
  - spatial extent of damage determined from scan image

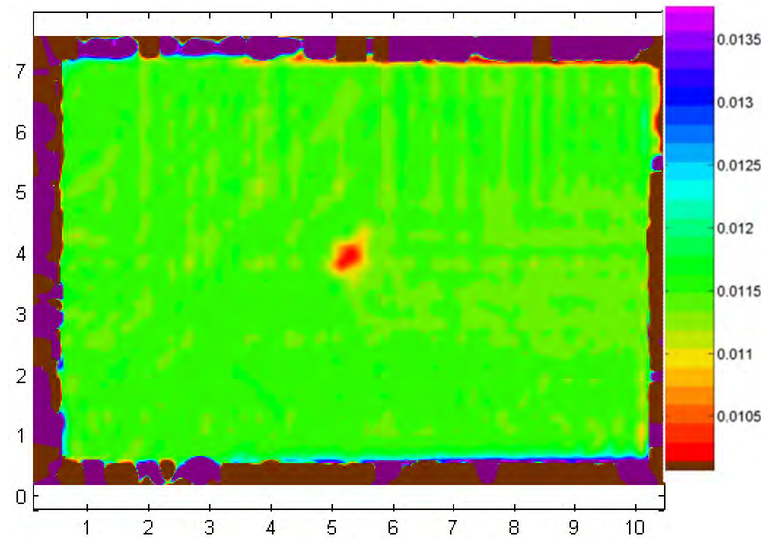


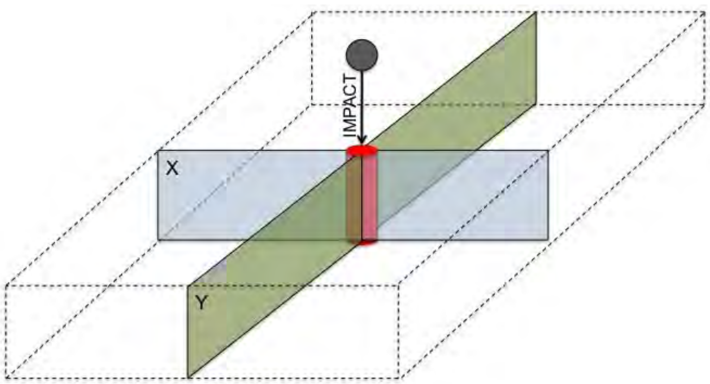
Volumetric Imaging of Composite Impact Damage

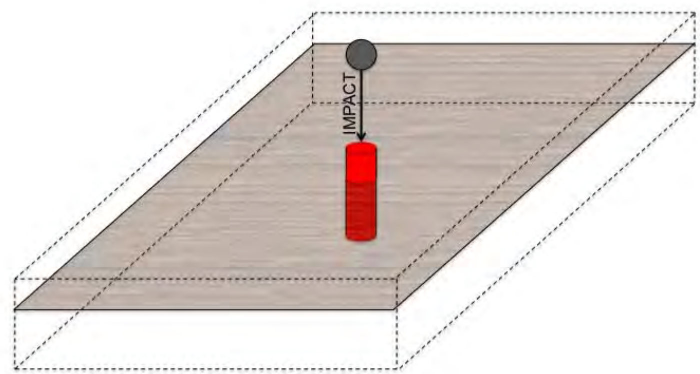
Sample provided courtesy of Lockheed Martin



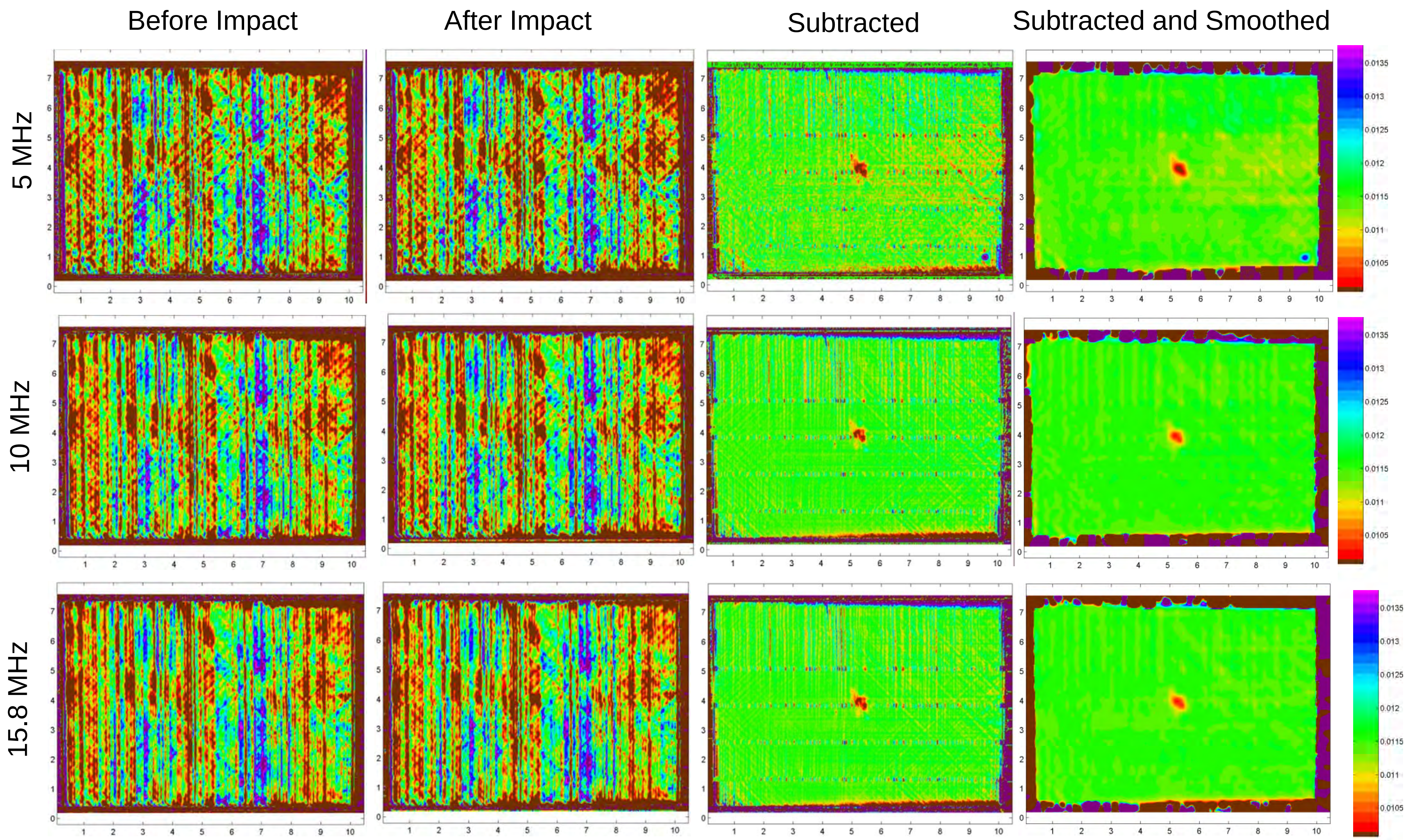
Representative MWM-Array Scan Image





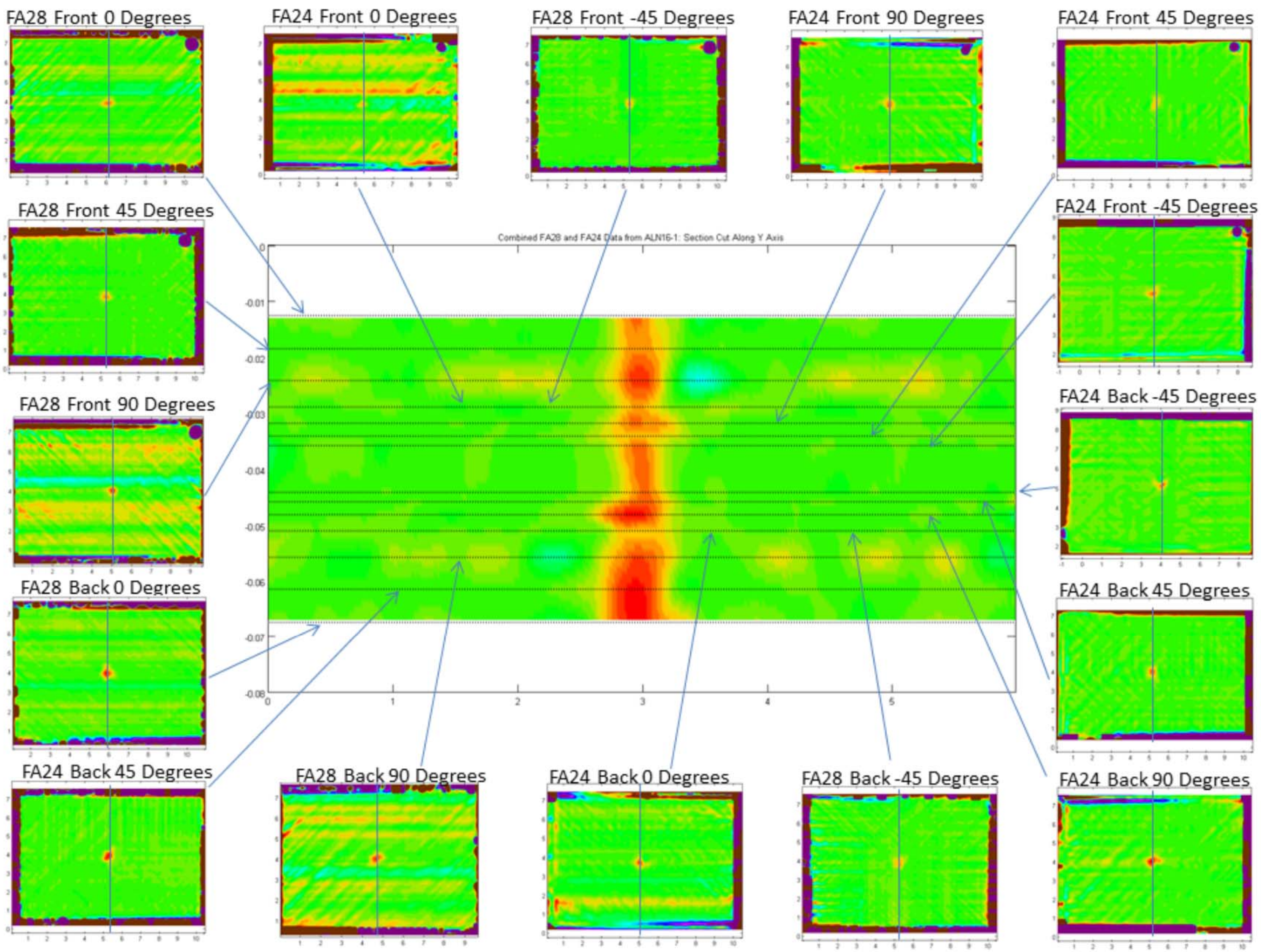


Representative Quasi-isotropic Panel Scan Images



Summary of Scans

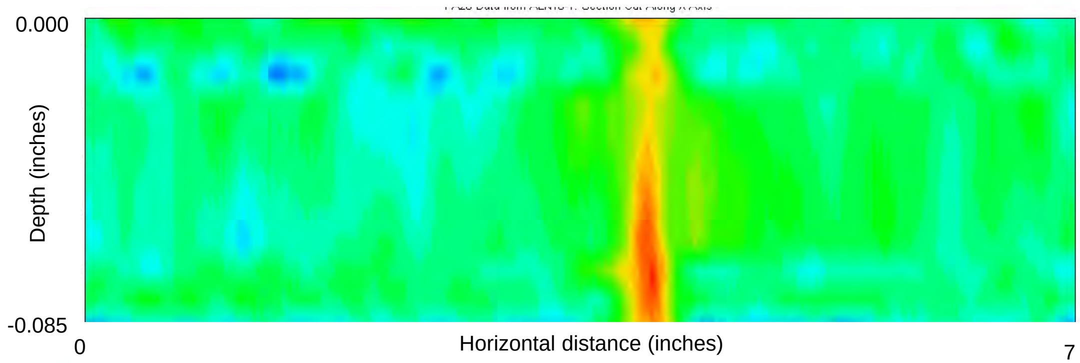
- Individual scans combined together to create composite cross-sectional view



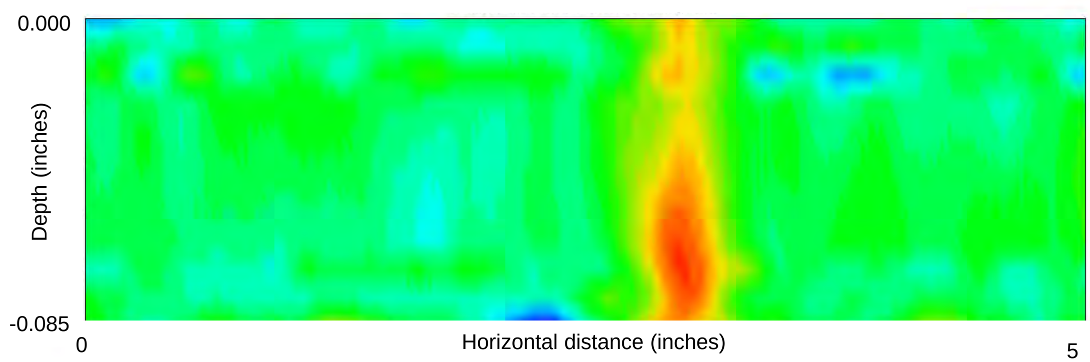
Cross Sectional Images: Panel 1, Low Impact Level

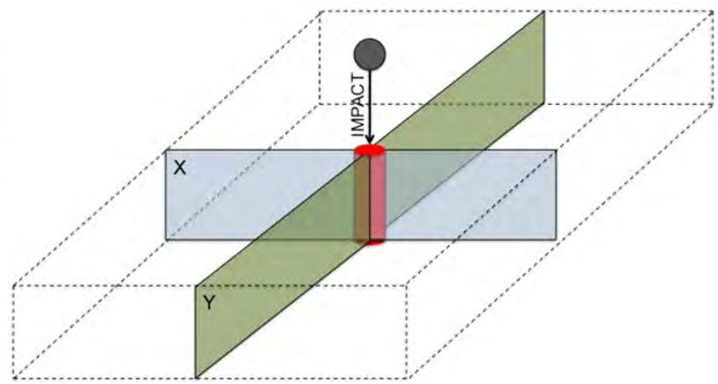
MWM-Array FA28 Data for 0.085-in. thick panels

Cross Sectional View along X-axis



Cross Sectional View along Y-axis

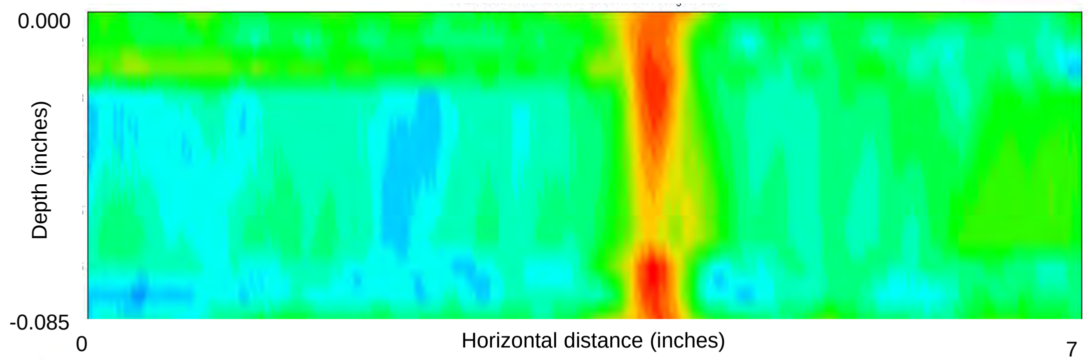




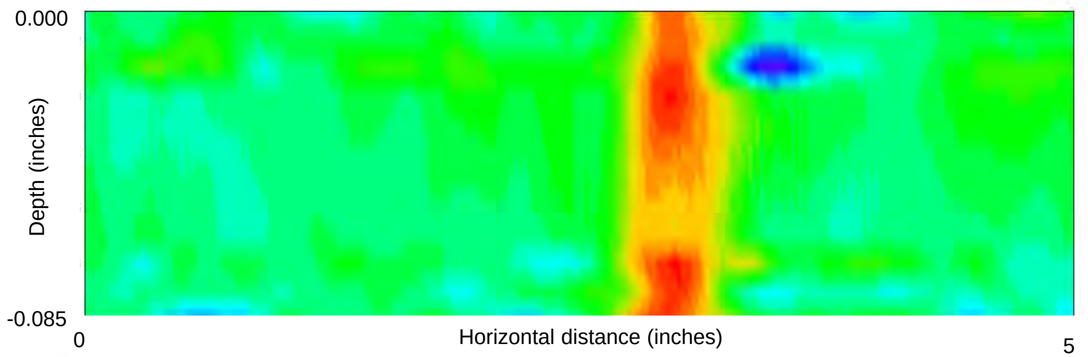
Cross Sectional Images: Panel 2, Medium Impact Level

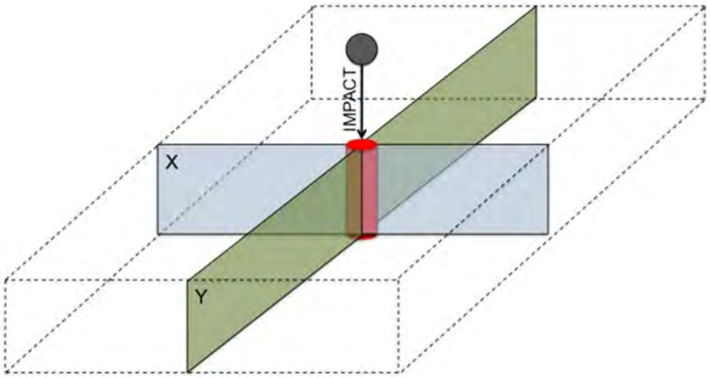
MWM-Array FA28 Data for 0.085-in. thick panels

Cross Sectional View along X-axis



Cross Sectional View along Y-axis

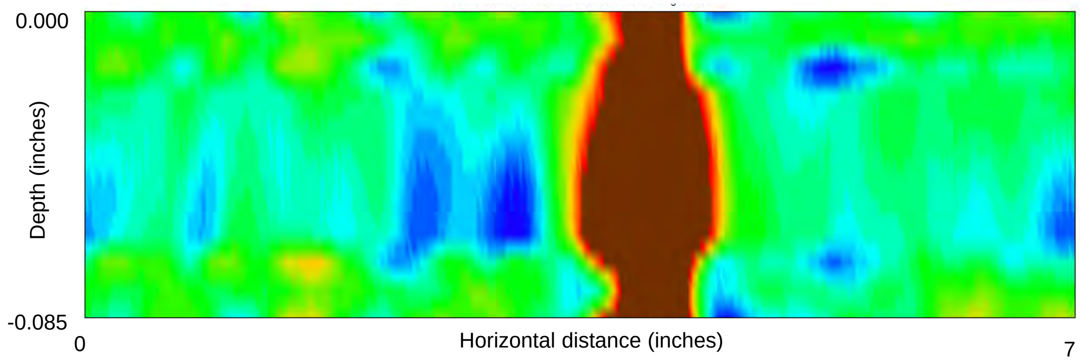




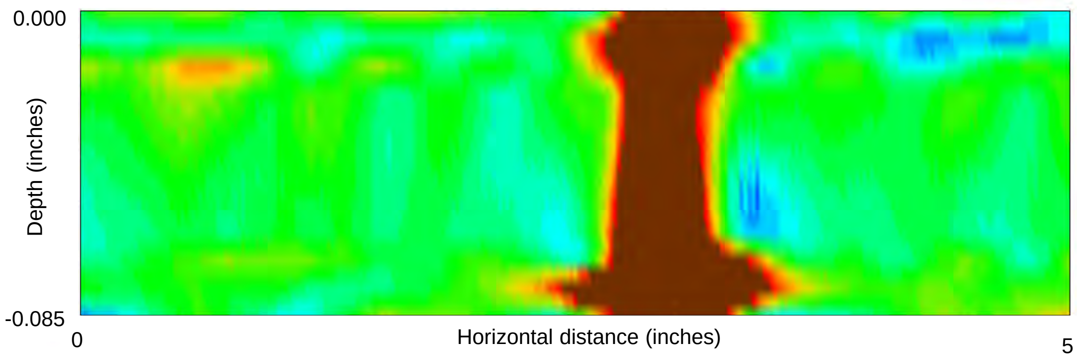
Cross Sectional Images: Panel 3, High Impact Level

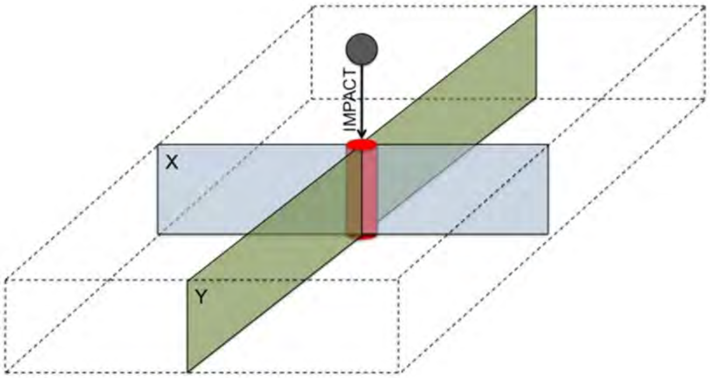
MWM-Array FA28 Data for 0.085-in. thick panels

Cross Sectional View along X-axis



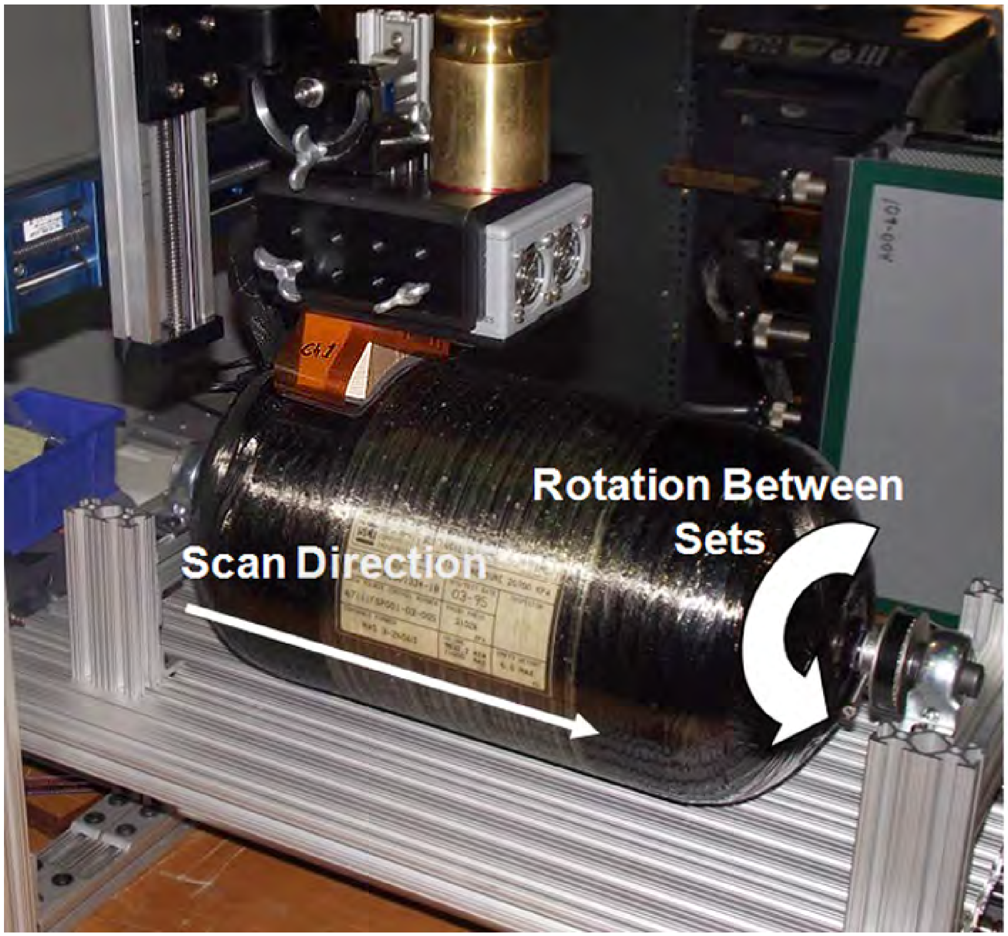
Cross Sectional View along Y-axis

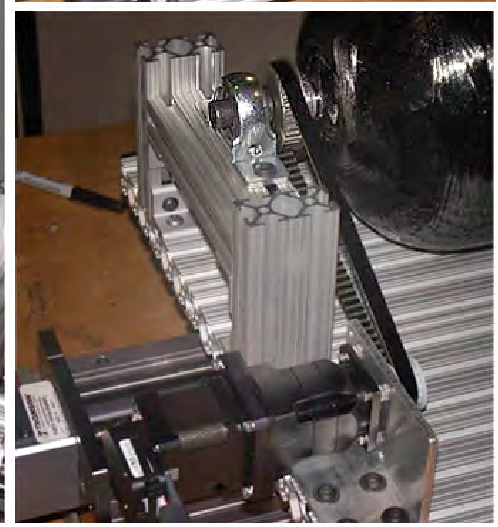




Composite Overwrapped Pressure Vessels (COPVs)

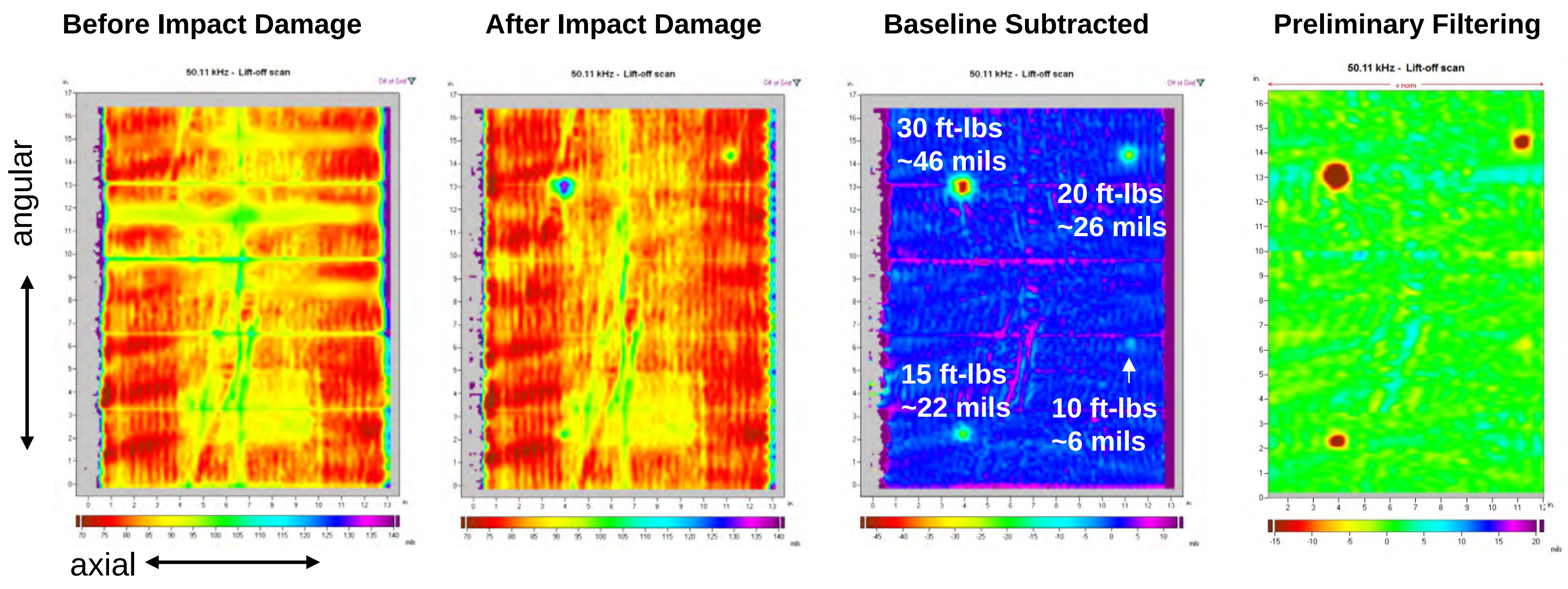
- Helical wraps at several different orientations with a metallic liner
- Eddy current scans can image both liner and composite properties



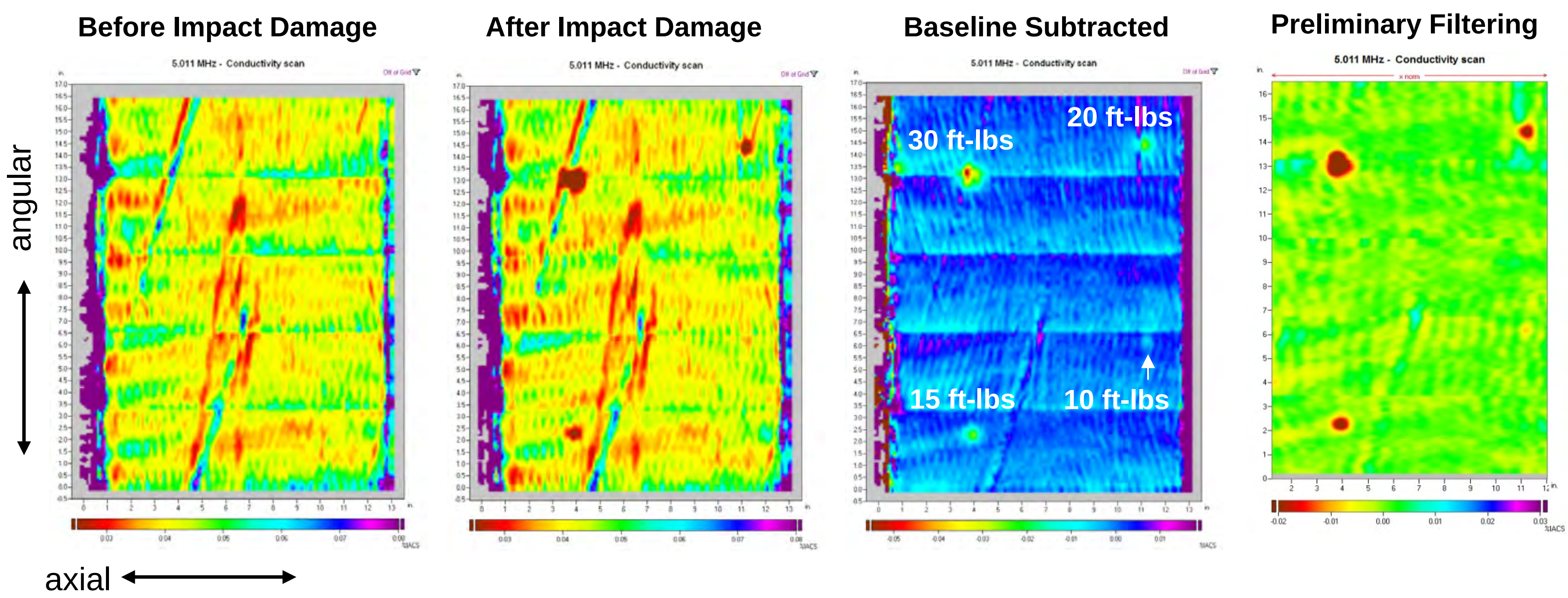
COPV: Low Frequency Inspection

- 50 kHz
- 90° drive orientation with 0.066-in. thick overwrap
- At this frequency the sensor responds primarily to the liner
- Effective lift-off images show dents in liner
- Higher impact energy results in larger dents in the aluminum liner



COPV: High Frequency Inspection

- 5 MHz
  - At this frequency more of the signal related to the composite overwrap properties
- 90° drive orientation with 0.066-in. thick overwrap
- The conductivity images show significant spatial variations in the overwrap properties
- Changes in the effective conductivity images highlight the damage



Summary

- An eddy current extension to a micromechanical model has been developed for conducting fiber composites
- Layered-media models have been developed to account for anisotropic properties
- Measurements have verified the orientation dependence of the sensor response and field spatial variations in the vicinity of the sensor
- Ongoing work is aimed at refining the models and correlating electrical properties to the properties of interest, such as:
  - Fiber density variations within a ply
  - Stress dependent changes in the electrical properties
  - Volumetric assessment of stress and damage conditions

Questions?

The views and opinions expressed in this presentation are those of the authors and do not necessarily represent official policy or position of JENTEK Sensors, Inc., or any Department of the U.S. Government.

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