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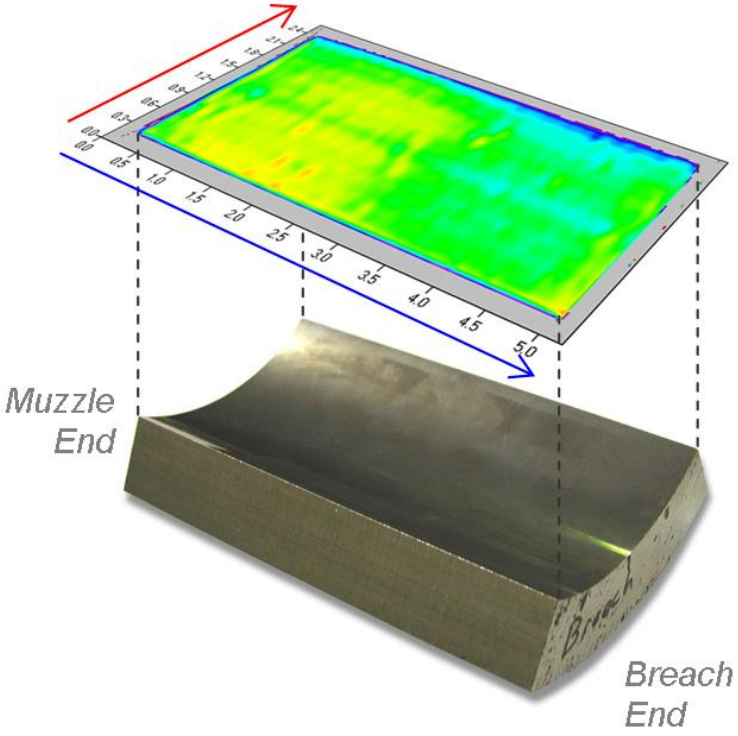
Review of Progress in Quantitative NDE
Bowdoin College, Brunswick, ME

July 31-August 5, 2005

Quality Assessment of Refractory Protective Coatings using Multi-Frequency Eddy Current MWM-Arrays



Vladimir Zilberstein, Leslie Evans,
Carolene Huguenin, David Grundy,
Yanko Sheiretov, Neil Goldfine,
JENTEK Sensors, Inc.,
and
Christopher Mulligan
U.S. Army Armament Research,
Development & Engineering Center, Benét Laboratories

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Erosion and Thermal Shock Resistive Coatings

- Increased range, rate of fire, and muzzle velocity have resulted in **increased wear and erosion problems** in gun tubes coated with electroplated chromium
- Dry physical vapor deposition (PVD) processes such as cylindrical magnetron sputtering (CMS) are being developed to increase the service life of gun tubes and address the environmental considerations associated with electroplating chromium
- Quantitative NDE of coatings deposited by CMS is crucial to the continued development and statistical process control of these emerging manufacturing processes

NEED:

- Coating thickness measurement
- Verification of coating phase composition

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Objectives

1. Provide nondestructive characterization of the following properties of CMS deposited tantalum coatings on gun barrel steel:
   - Tantalum coating thickness
   - Phase composition, i.e., α-, (α+β)- or β-phase Ta
     (α – good)
   - Imaging/identification of lower conductivity areas (indicating presence of β-phase tantalum)
2. Develop scanner for gun barrels

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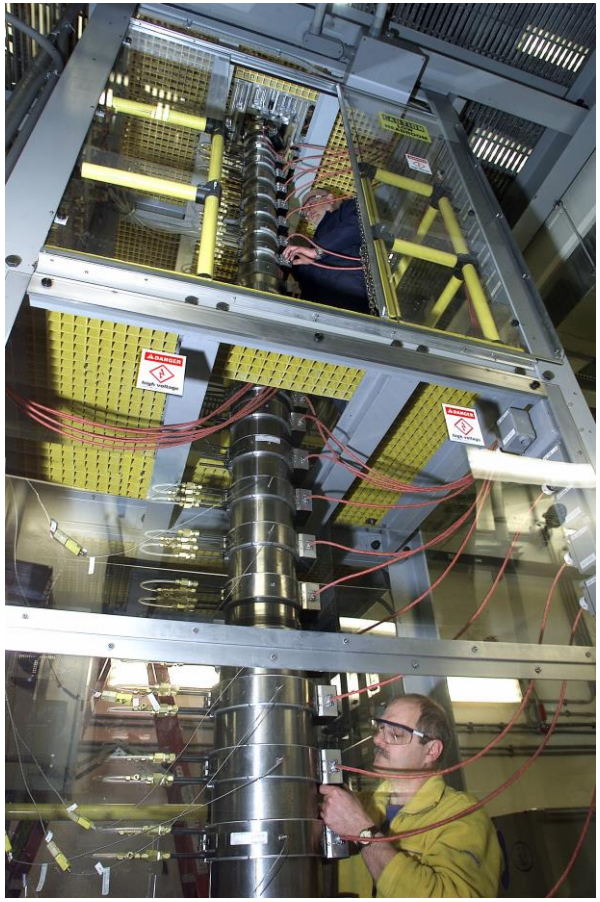
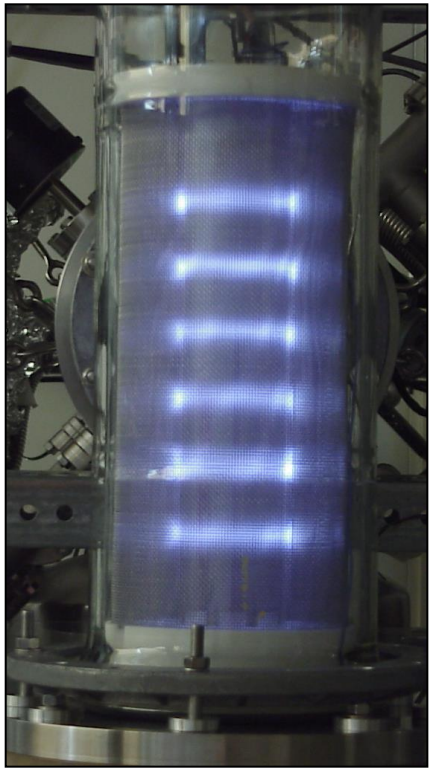
Cylindrical Magnetron Sputtering

(Low temperature deposition)





Full length gun barrel sputtering chamber

"Plasma rings"

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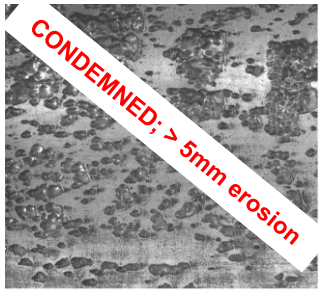
Perspective

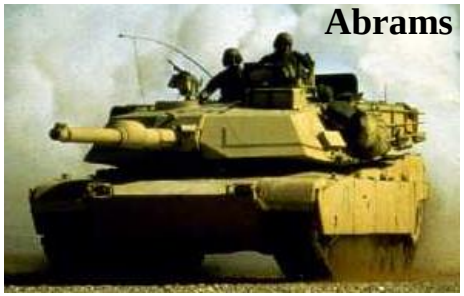
Large Caliber Gun Firing Environment

- Internal Pressure can exceed 100 ksi (690 MPa)
- Peak gun bore T can exceed 1400C
- Highly transient nature of gun firing results in extreme thermal shock environment (e.g. 200x more aggressive than in the gas turbine industry).
  Adhesion is paramount.
- Aggressive propellant by-products such as CO & H_2S
- Coatings must be deposited at T < ~350C

ABRAMS 120mm Gun Barrel
101 M829 rounds
771 Total rounds



ABRAMS 120mm Gun Barrel
39 Candidate high energy rounds
214 Total rounds



(Developmental)

(Developmental)

(Developmental)

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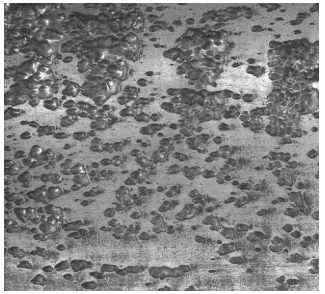
Why Cylindrical Magnetron Sputtering?

- Extend the life/performance of gun barrels, *reduce logistics burden, enhance lethality, cost avoidance*
- Most mature, next generation coating process for Lg Cal gun barrels
- Scaleable and flexible technology
- Preserves the beneficial residual compressive stresses in Lg Cal gun barrels
- Replace the current process, Cr electroplating, a hazardous process



Erosion in Gun Barrel

Toxic sludge from Cr plating

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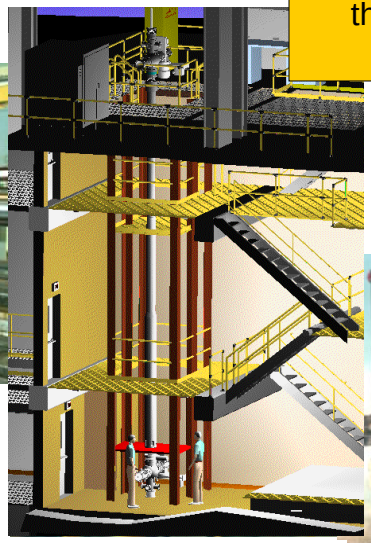
LG Cal Gun Barrel Manufacturing Sequence

CMS will not alter barrel manufacturing sequence

Billet → Rotary Forge → Heat Treat → Rough Machining → Autofrettage → Post-Autofrettage Thermal Soak → Finish Machining → CMS → MWM → Ship

Rotary Forging

Machining



CMS

CMS technology can be “plugged in” to the current barrel manufacturing process w/o alteration

Fielding

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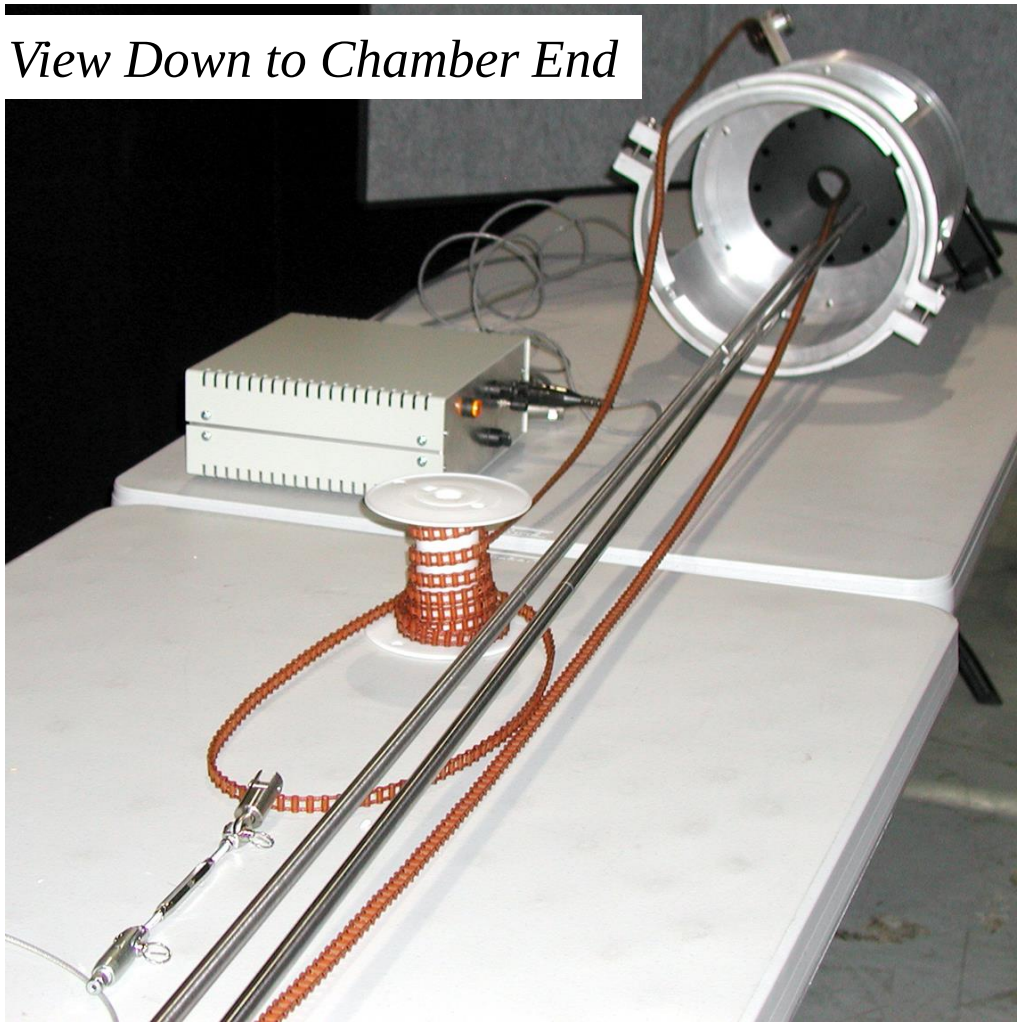
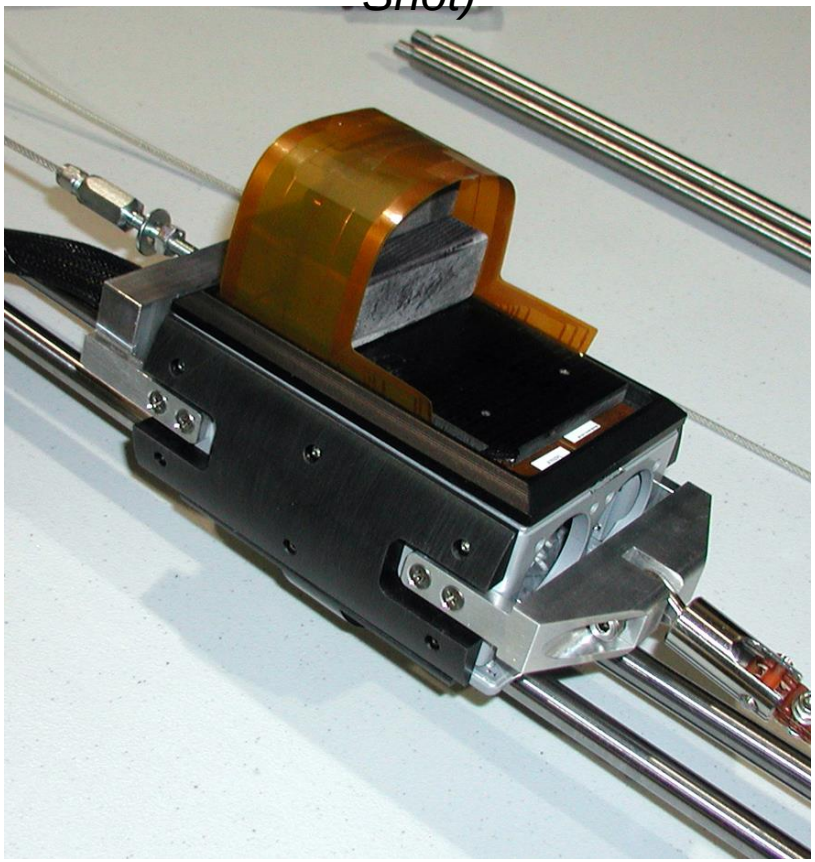
Gun Barrel Inspection Fixture

View Down to Chamber End



Adapted MWM-Array Probe (Angle Shot)



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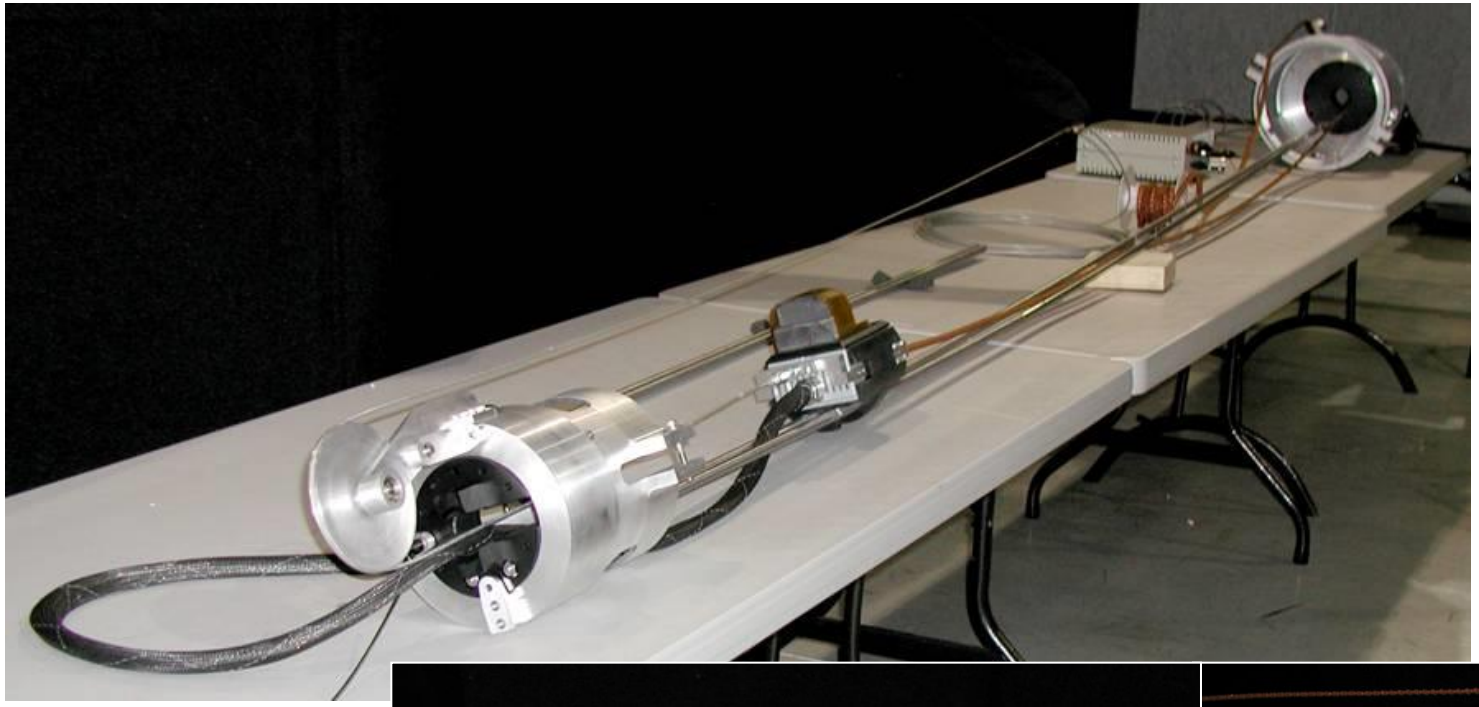
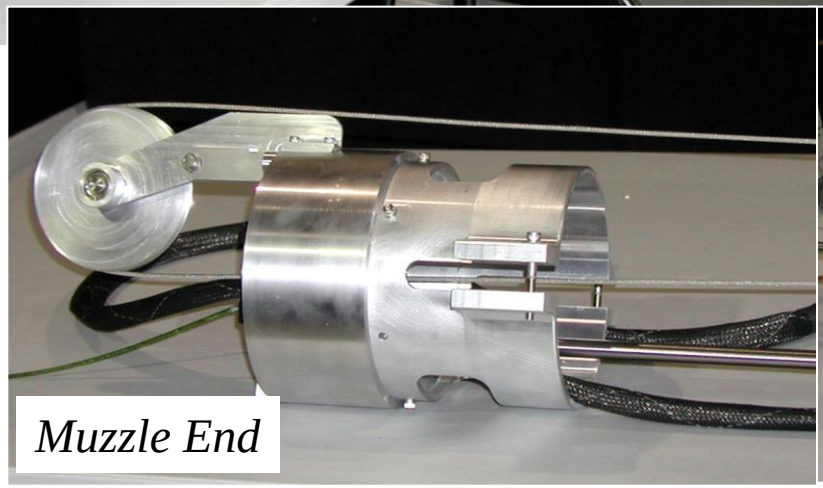
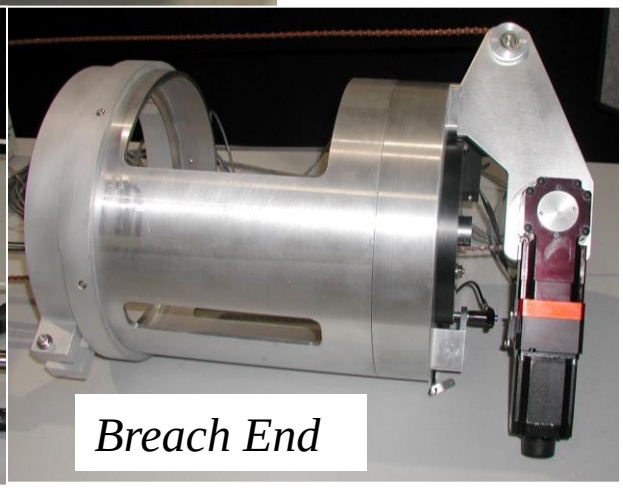
Gun Barrel Inspection Fixture







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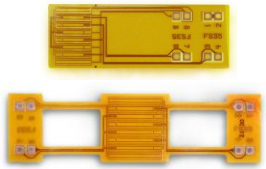
Measurement Method

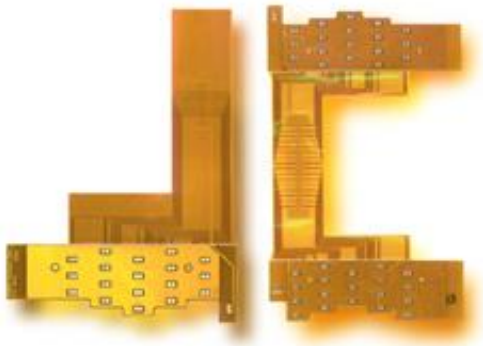
- Multifrequency electrical conductivity measurements
- Meandering Winding Magnetometer (MWM)
- Scanning MWM-Arrays
- Multivariate inversion methods for multiple property measurements

Single Channel **MWM** Probe with Interchangeable Tips

Single channel MWM



Multi-channel MWM-Arrays



JENTEK GridStation Setup with 39-Channel Instrument and 39-Channel **MWM-Array** Probe

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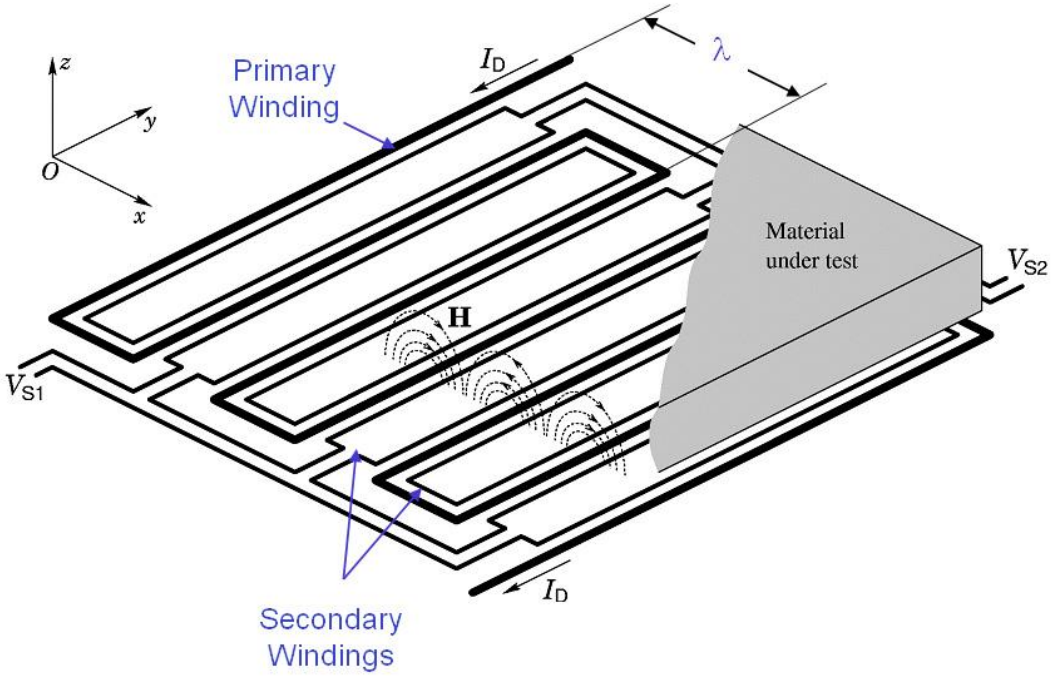
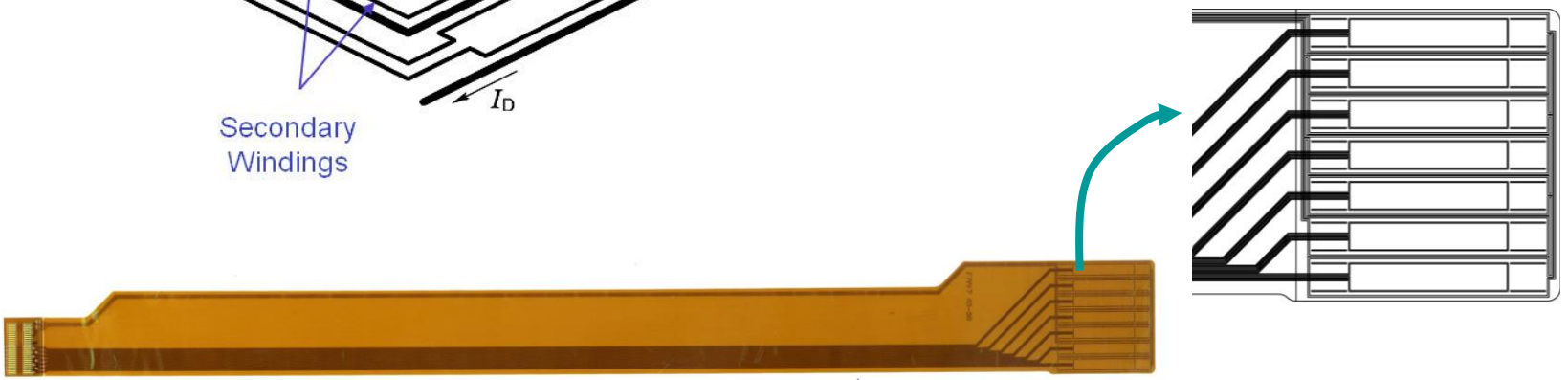
Meandering Winding Magnetometer (MWM®)



- Thin, flexible
- Conformable to complex geometries
- Designed to fit the physics-based model



Transfer Impedance = Secondary Voltage / Primary (input) Current

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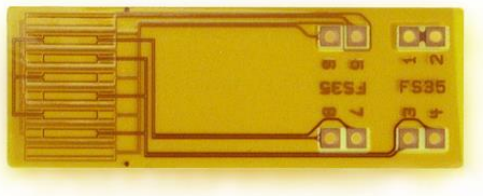
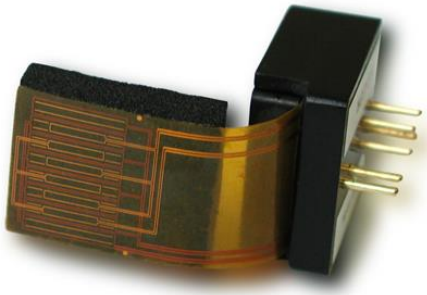
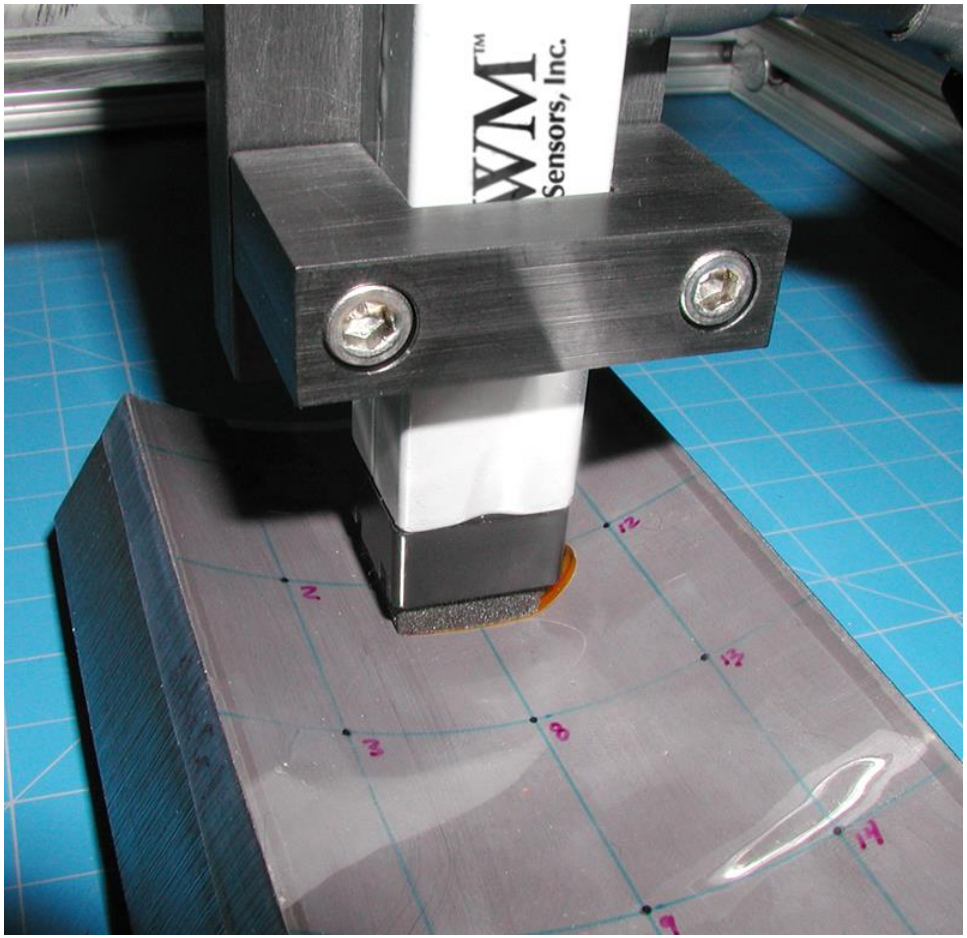
Single Channel Sensor MWM



FS35 MWM sensor



FS35 MWM sensor tip



FS35 probe fixture in use

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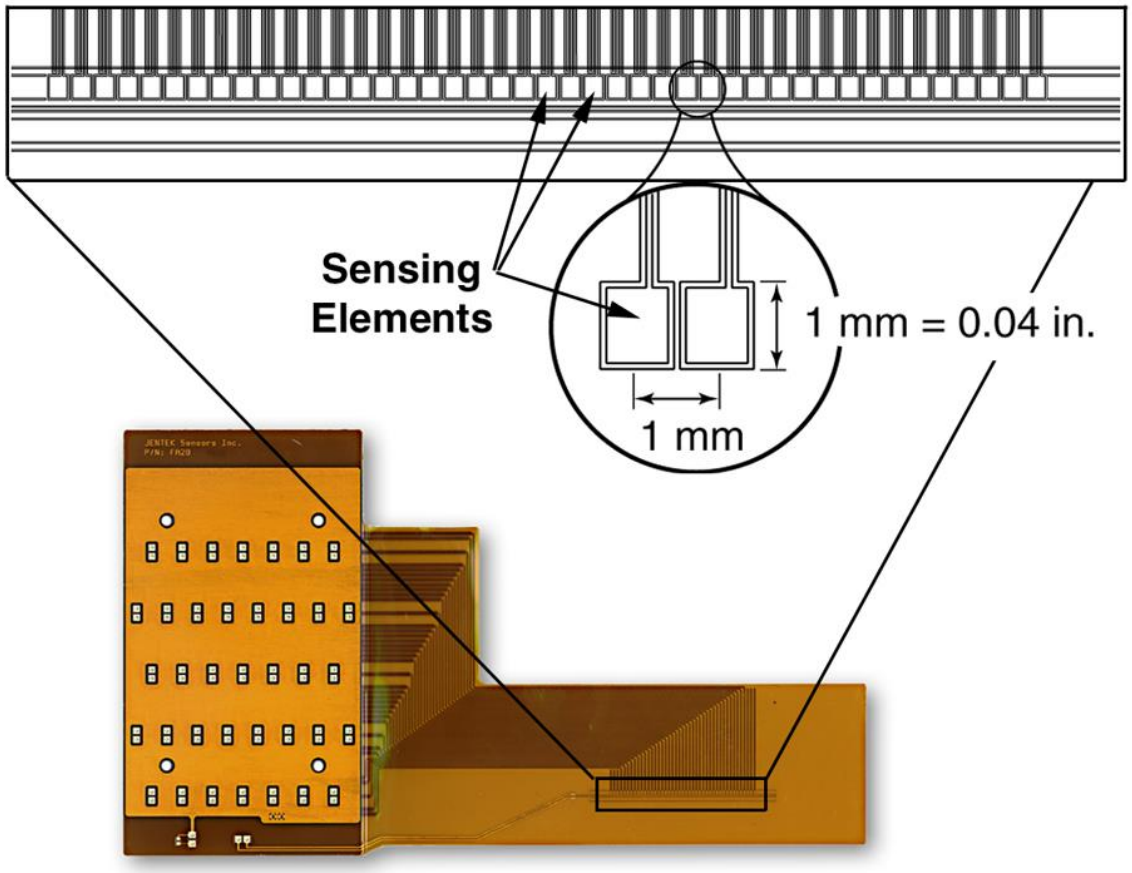
MWM-Array Sensor with 37 Channels (FA28)



- **Scan width = 37 sensing elements = 37 mm (1.48 in.)**

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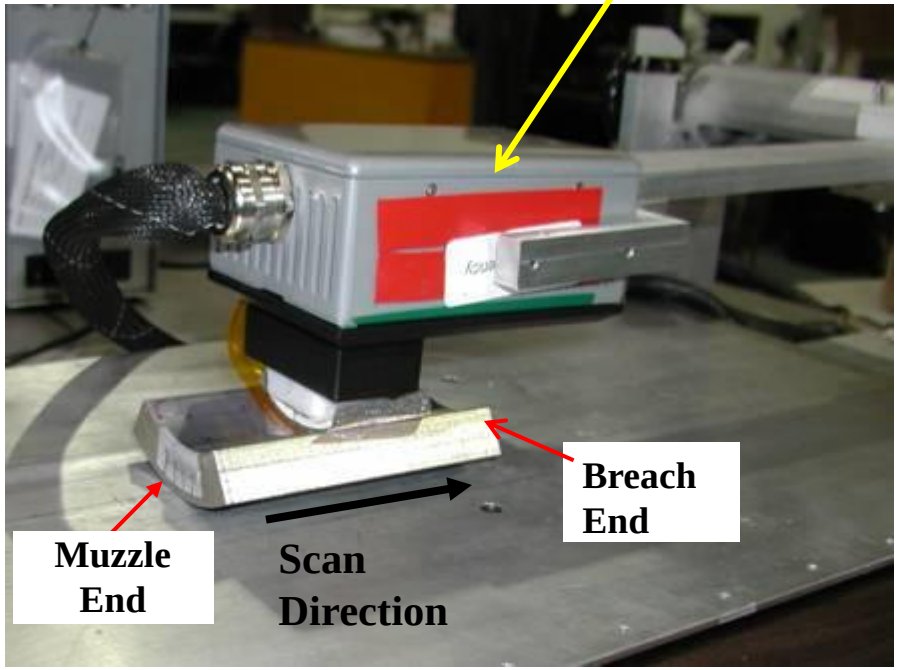
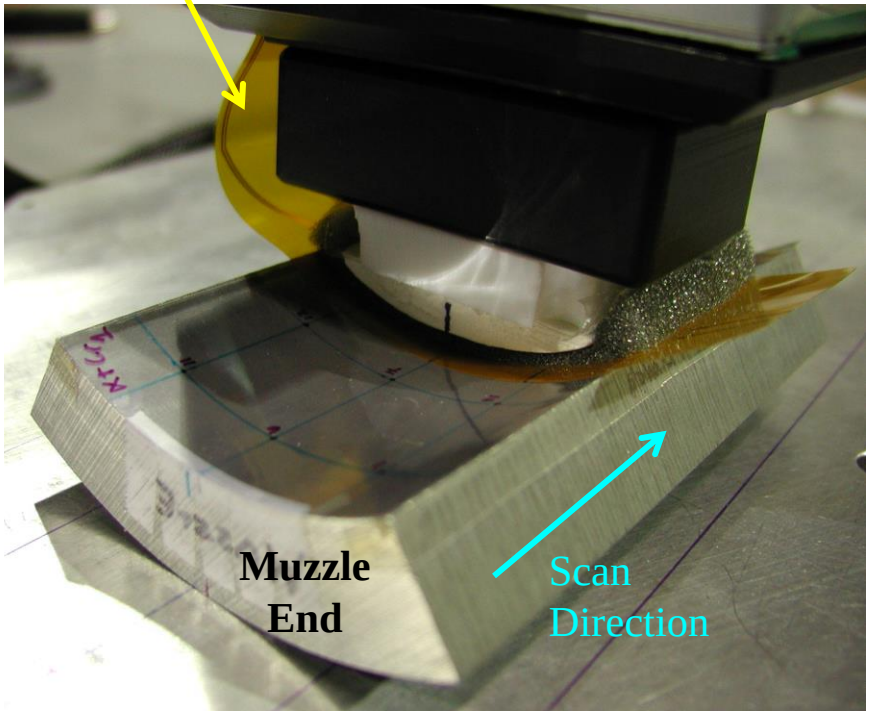
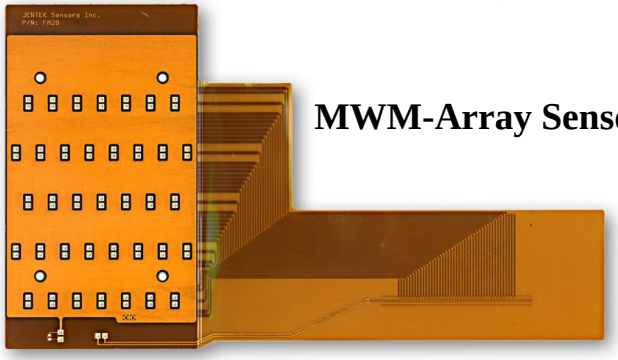
Scanning with Multi-Channel MWM-Arrays

MWM-Array probe



MWM-Array Sensor





MWM-Array Sensor FA28

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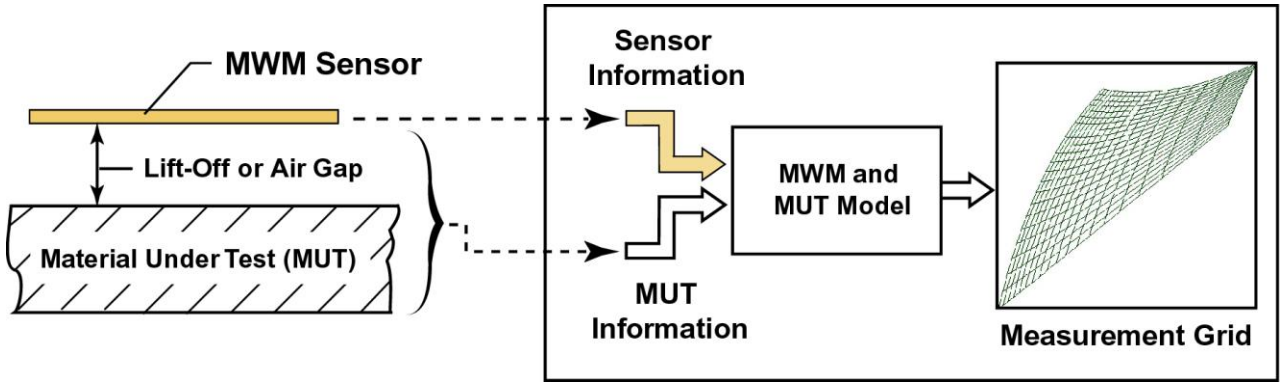
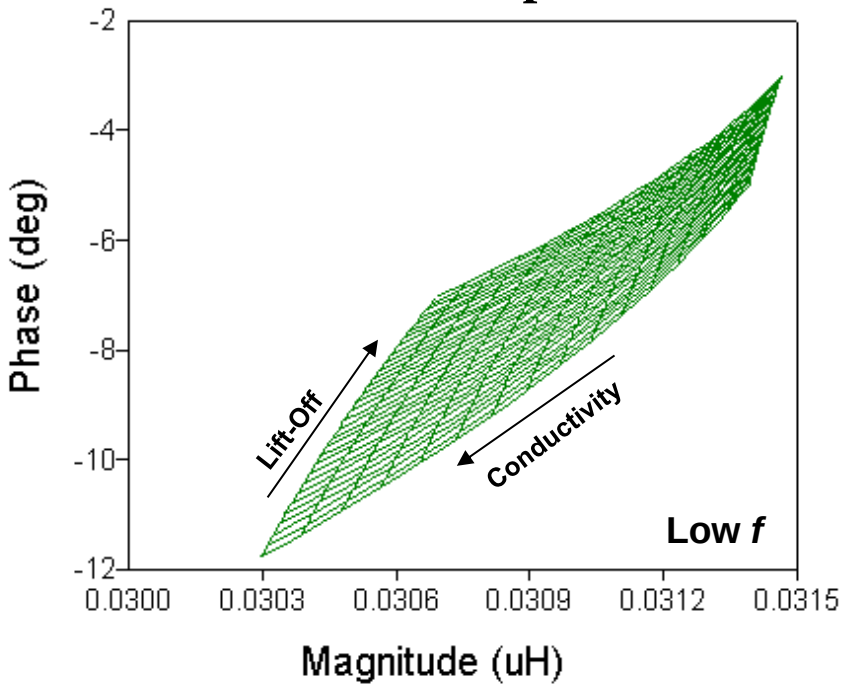
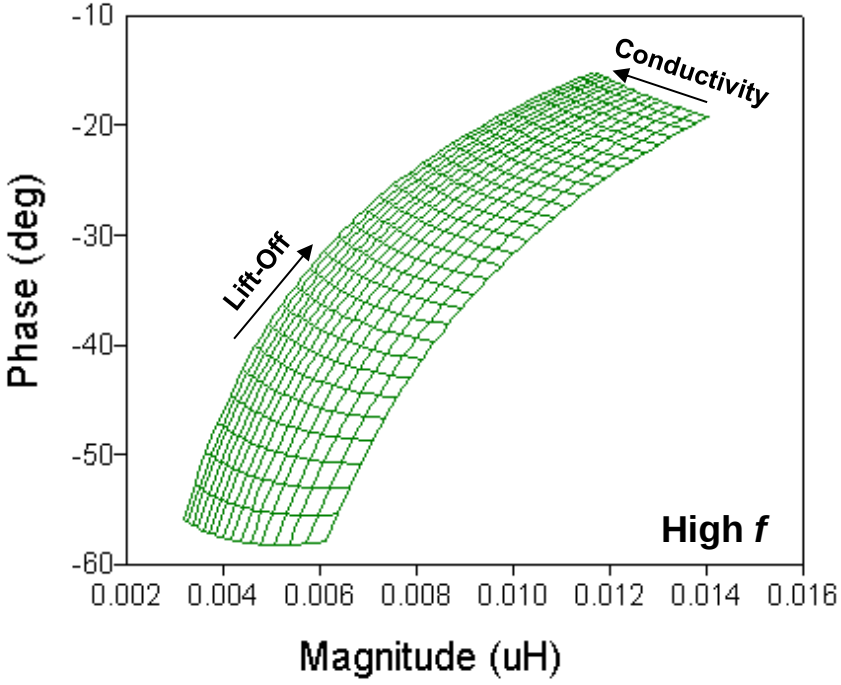
Conductivity / Lift-off Measurement Grids



Example Grids for the MWM-FS35 Sensor





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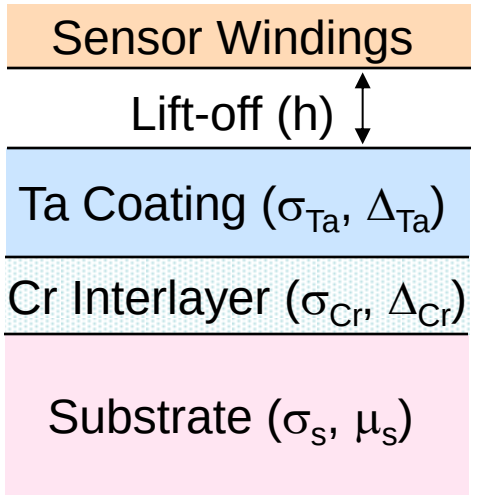
Measurement Grid Hyper-Cubes

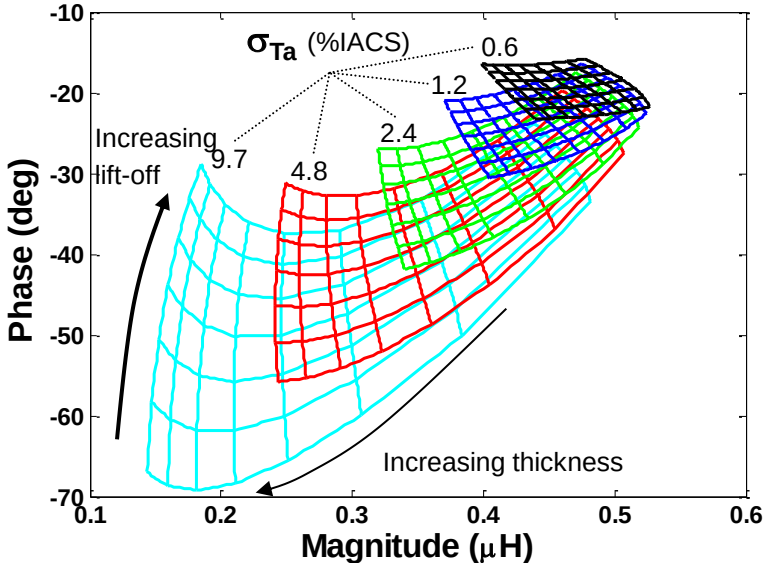
(patents issued and pending)

- A 3-D Lattice is a collection of 2-D grids
  - Tantalum conductivity, tantalum thickness, and lift-off (assuming values for substrate permeability and conductivity, and chromium interlayer thickness and conductivity)
- Approach:
  - Use lattices to find properties that are independent of frequency



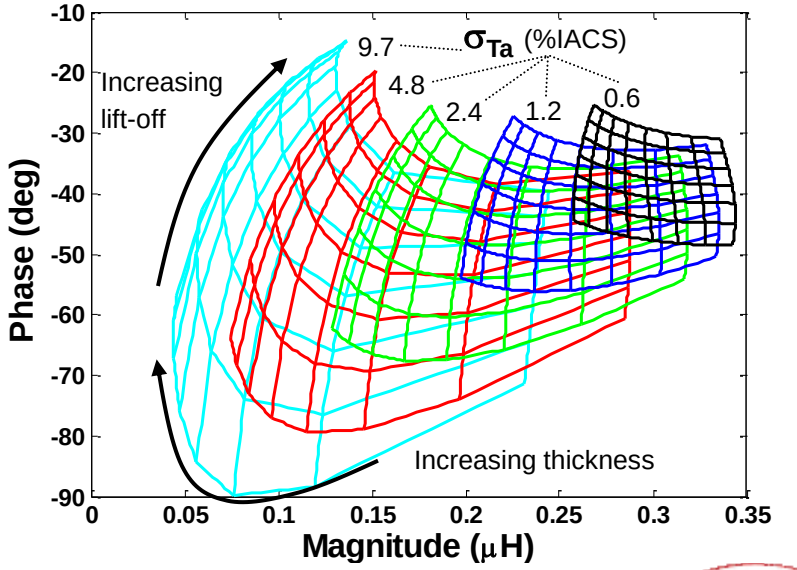
Low f σ_{Ta}-Δ_{Ta}- h Lattice

μ_s, σ_s, σ_{Cr}, Δ_{Cr} constant



High f σ_{Ta}-Δ_{Ta}- h Lattice

μ_s, σ_s, σ_{Cr}, Δ_{Cr} constant



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Analysis Model:

JENTEK's patented 4-unknown inversion method was used to characterize the properties of the tantalum coating and steel substrate. The four unknowns measured in this approach are:

1) Lift-off

2) Tantalum Coating Conductivity

3) Tantalum Coating Thickness

4) Steel Substrate Permeability

Substrate conductivity and chromium interlayer thickness and conductivity are assumed.

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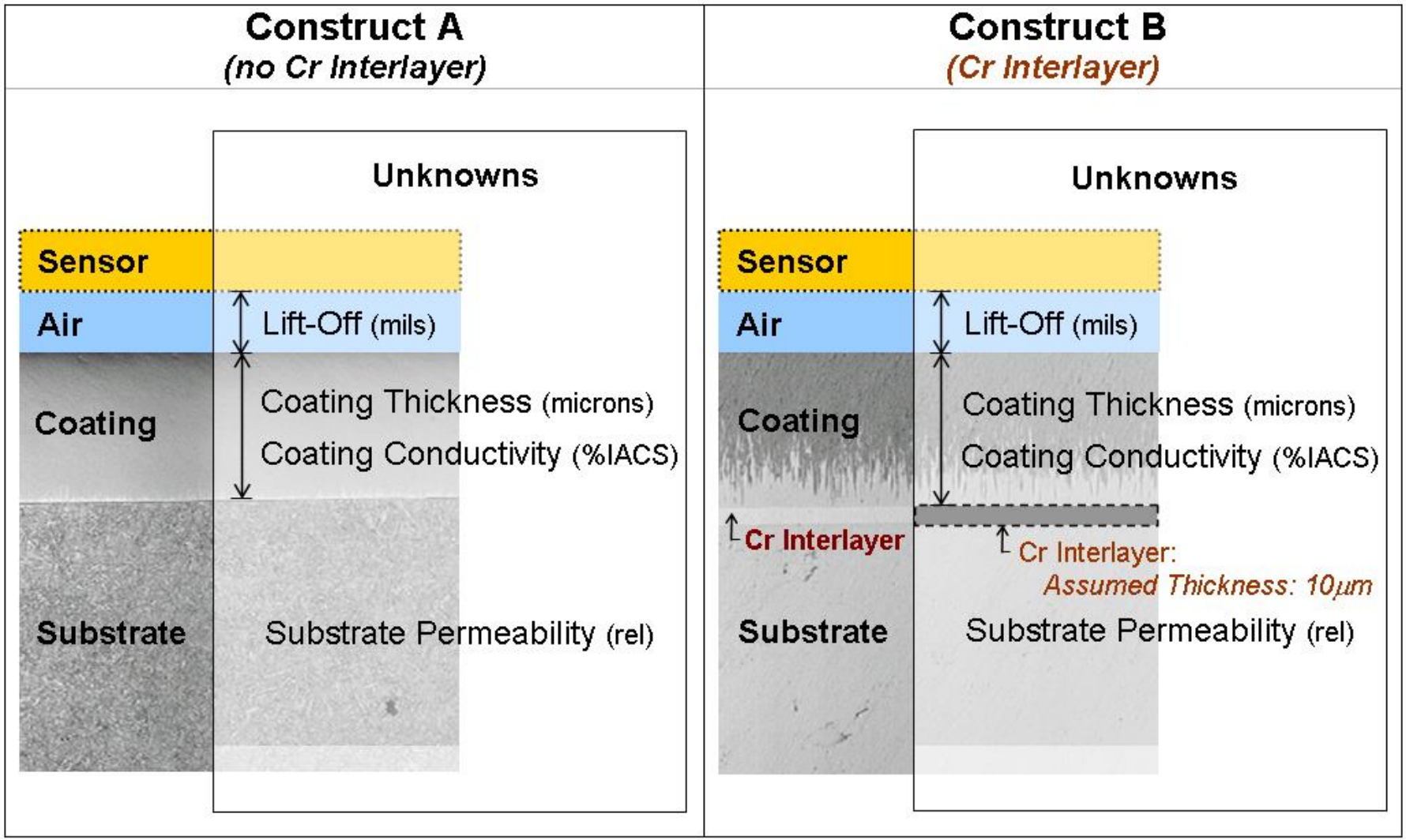
Schematics of 4-Unknown Constructs



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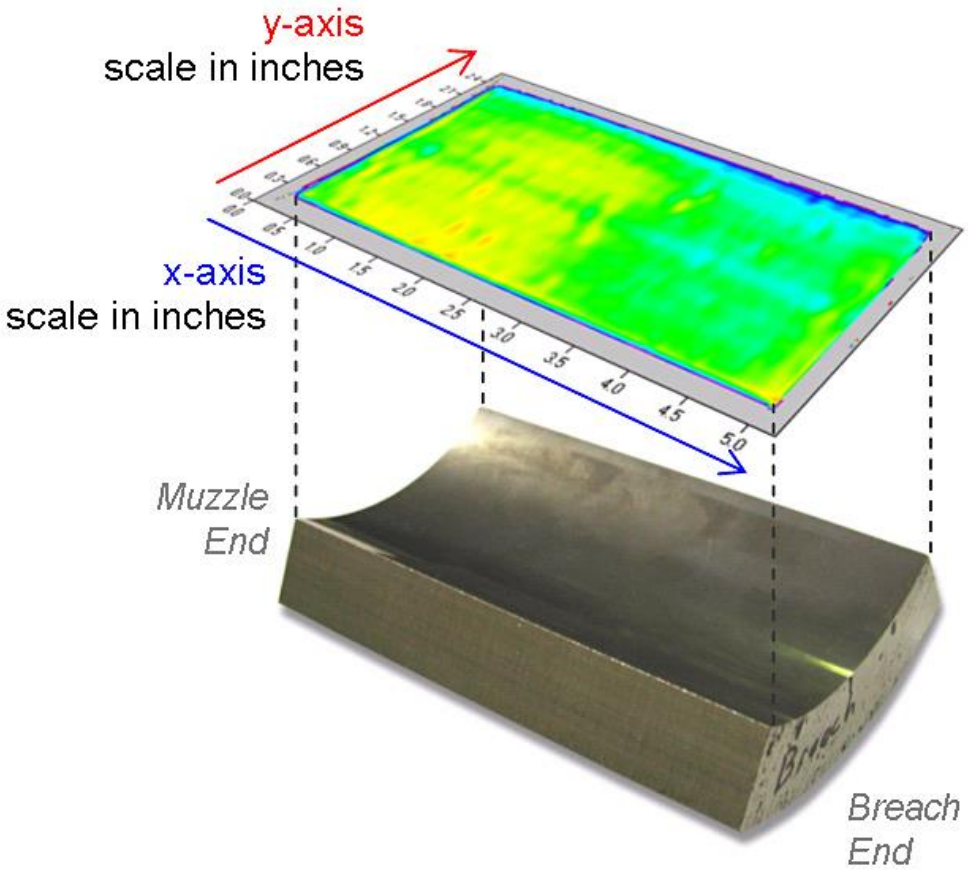
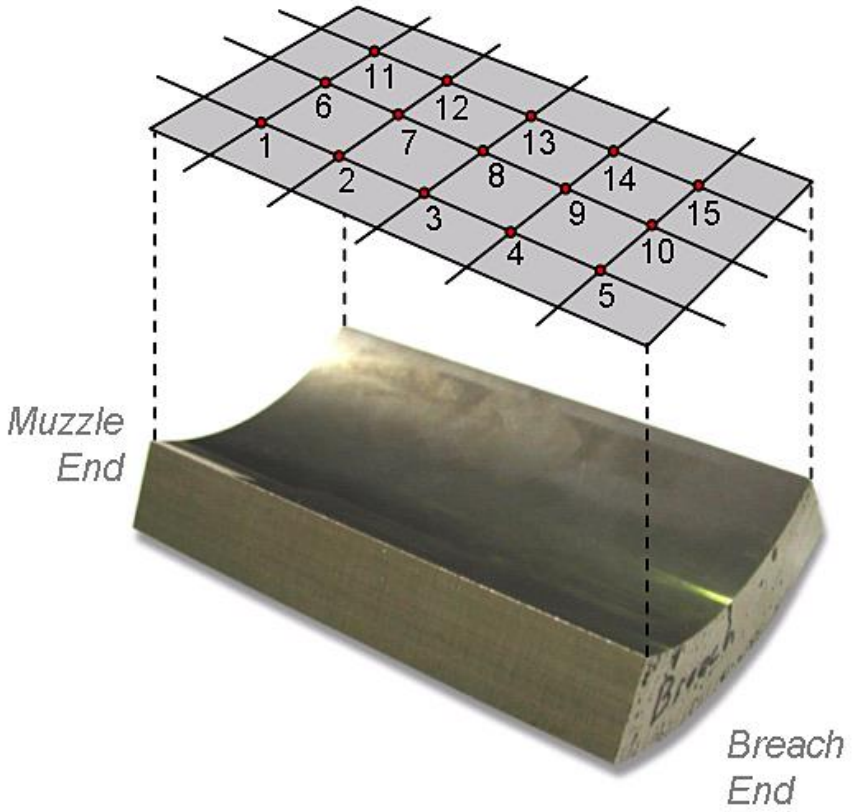
Example of MWM-Array Conductivity Image and Corresponding Sample





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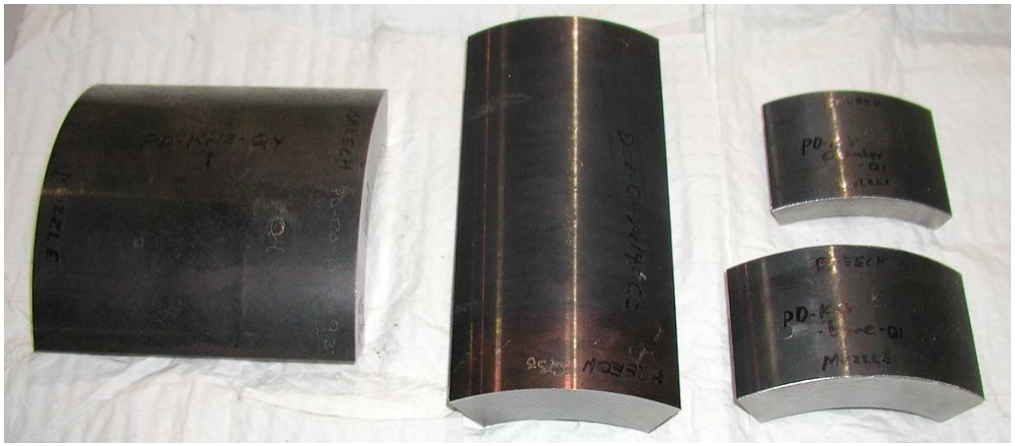
Matrix of the Samples Analyzed by JENTEK

			Sputtering Gas	
			Ar	Kr
Coating Composition	Majority α-Tantalum	100% Alpha	X	
		100% Alpha *with Cr*		X
		Mixed Phase (majority alpha)	X	
		Mixed Phase (majority alpha) *with Cr*		X
	Majority β-Tantalum	Mixed Phase (majority beta)		
		Mixed Phase (majority beta) *with Cr*		
		100% Beta	X	
		100% Beta *with Cr*		

Samples



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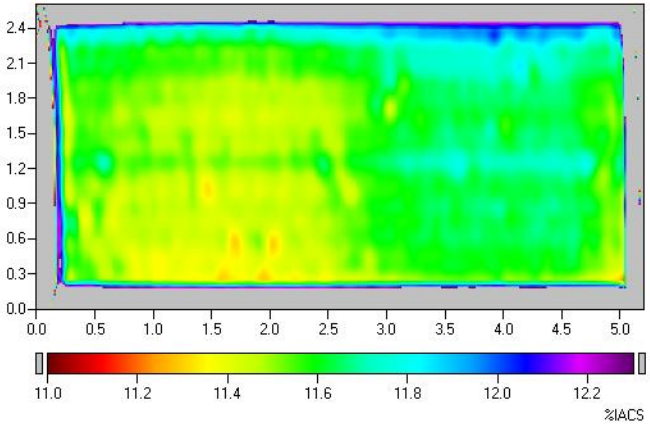
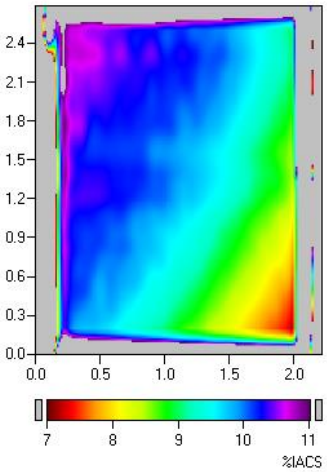
Examples of Coating Conductivity Images
(Samples Sputtered in Krypton)

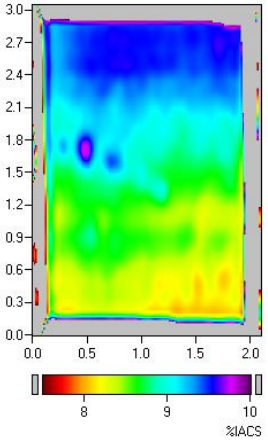
Sample 4: α-Phase Tantalum with Cr Interlayer



Sample 6: (α + β) Tantalum with Cr Interlayer



Sample 7: (α + β) Tantalum with Cr Interlayer



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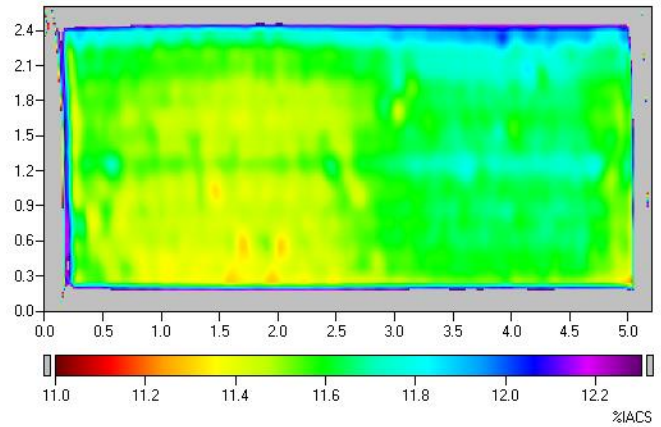
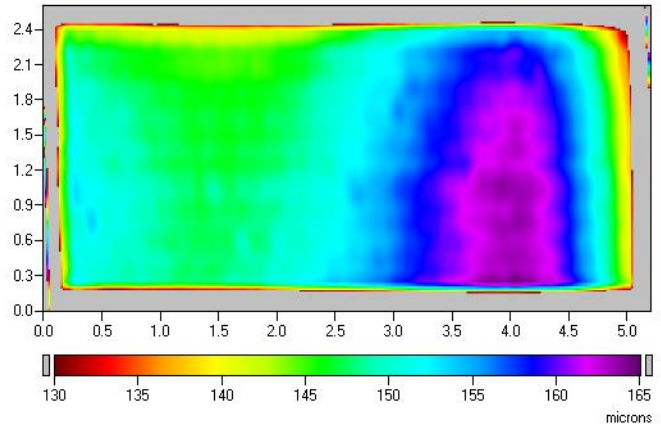
MWM-Array Images of Tantalum Coated Gun Barrel Steel

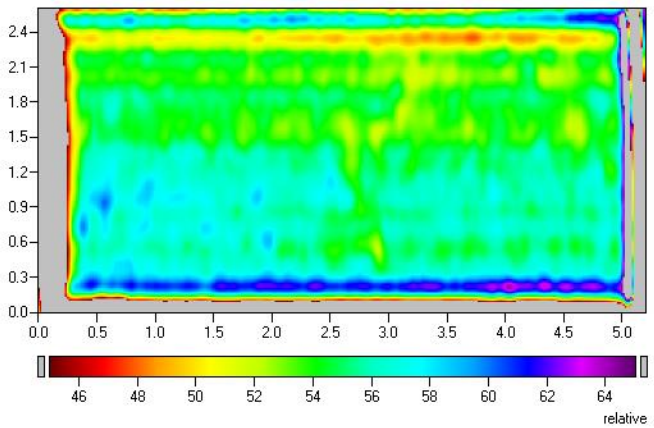
FA28 Scans of Sample PD-120-Kr10-Q1, 99% Alpha-Ta with Sputtered Cr Interlayer



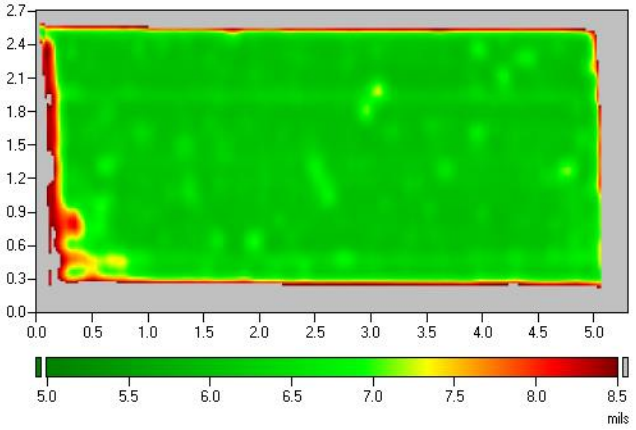
Tantalum Coating Conductivity *(%IACS)*



Tantalum Coating Thickness *(microns)*



Steel Substrate Permeability *(rel)*



Lift-Off *(mils)*

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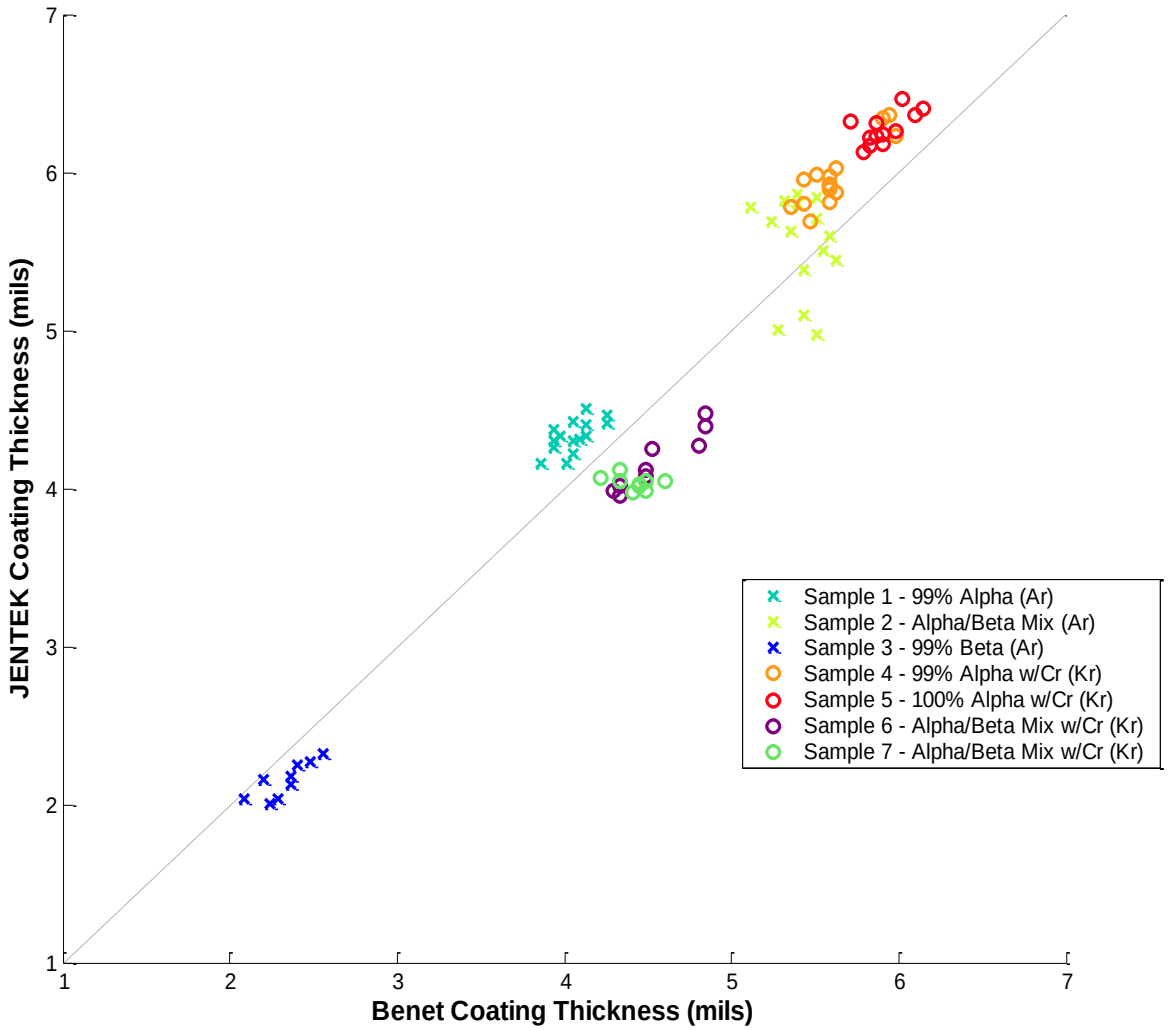
MWM-Array Measured Tantalum Coating Thickness Values



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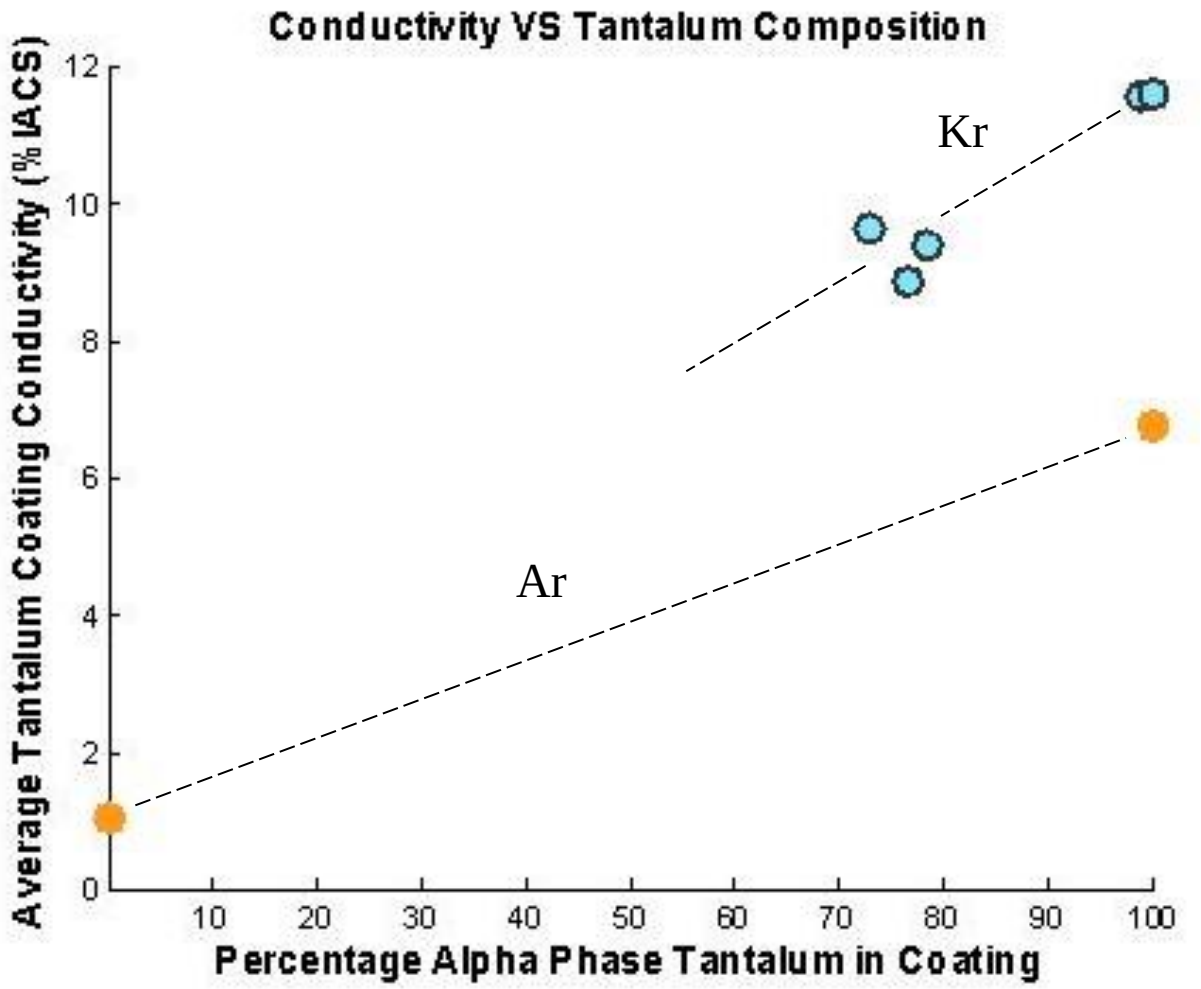
Conductivity vs. Phase Composition for Tantalum Coatings



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Conclusions

- MWM sensors and MWM-Arrays can measure the thickness of tantalum coatings sputtered on gun barrel steel
- MWM sensors and MWM-Arrays can measure the electrical conductivity of tantalum coatings on gun barrel steel with & without chromium interlayers
  - ✓ Relative conductivities of pure α-phase and mixed (α+β) phase regions depend on the sputtering gas. Pure α-phase conductivity values are significantly different for coatings processed in argon vs. those sputtered in krypton, e.g., 6.74% IACS in the case of argon and about 11.5% IACS in the case of krypton
  - ✓ Assuming a priori knowledge of the process gas, MWM sensors & MWM-Arrays can detect and determine the extent of lower conductivity regions containing β-phase
- System is currently in pilot testing on 40” and 12” gun barrel sections. Also, successfully tested on full length 5 m large caliber gun barrel.