Electric Potential and Electric Field Imaging with Dynamic Applications

2017 Research Award for Innovation

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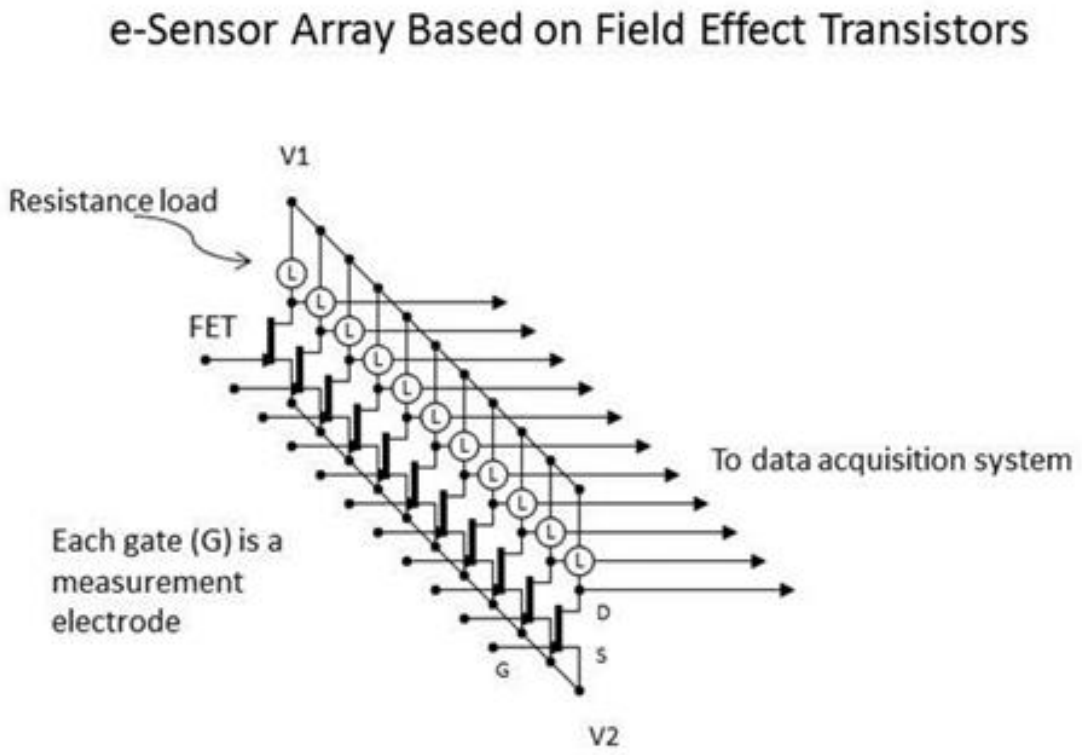
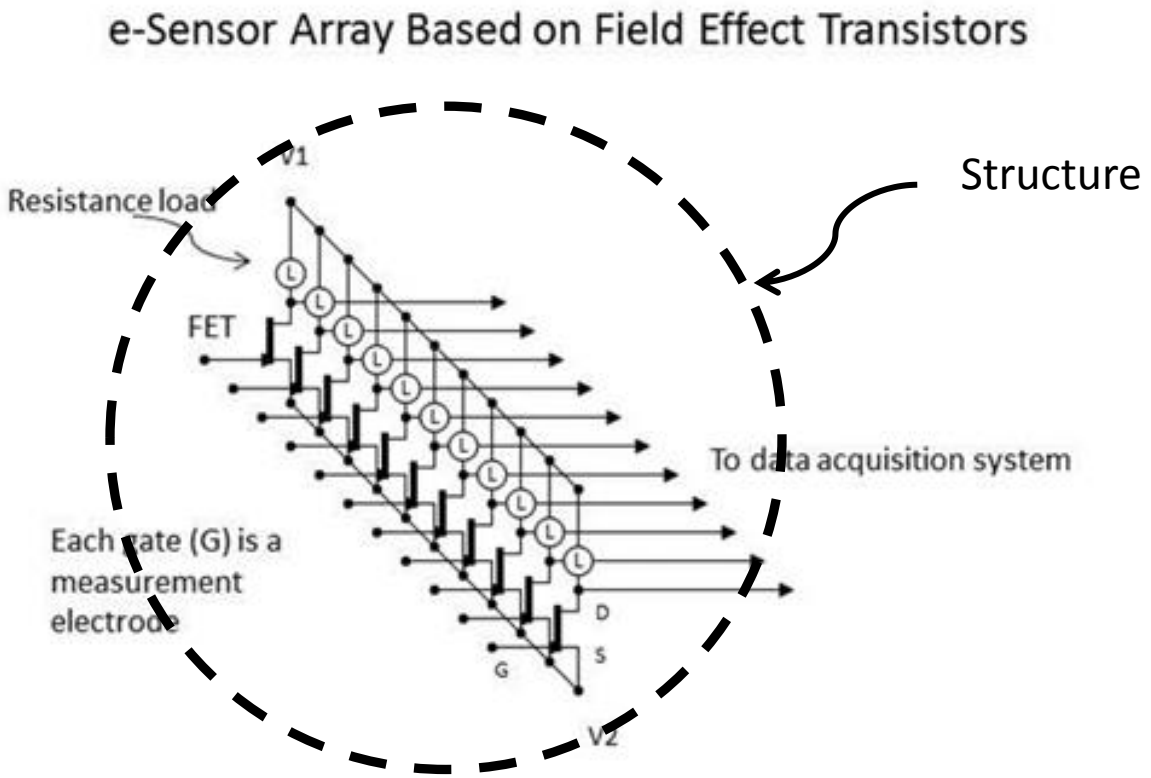
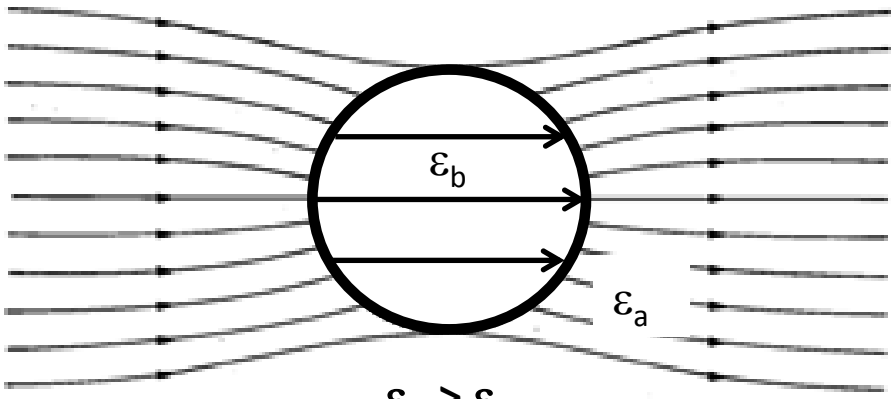
Background

- **NDE historically has focused technology development in propagating wave phenomena:**
  - X-ray, ultrasonic, microwave, thermal, terahertz, and eddy current
  - Little attention to the field of electrostatics and emanating electric fields.
- **Interest in evaluating the integrity of wire insulation in aircraft and aerospace systems**
- **This work is based on the original electric field sensor (e-Sensor) work disclosed by Generazio (2002).**

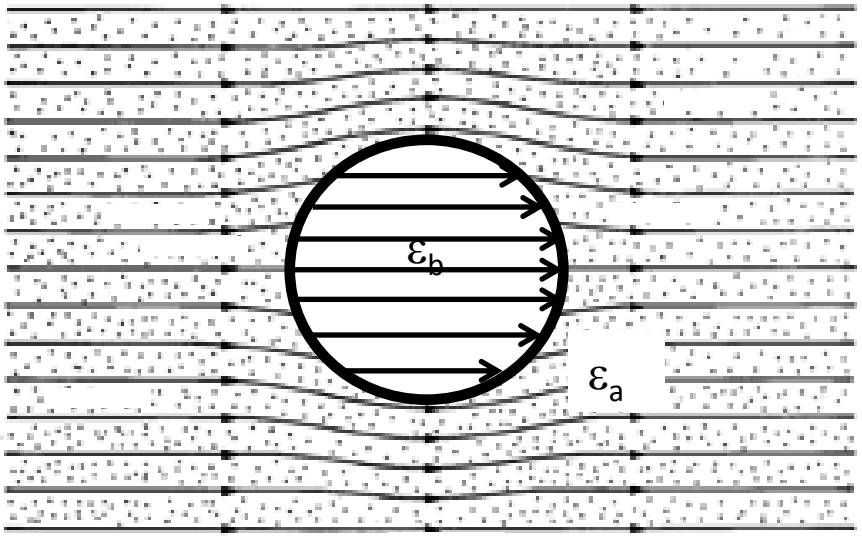

e-Sensor Array Based on Field Effect Transistors
V1
Resistance load
FET
To data acquisition system
Each gate (G) is a measurement electrode
D
S
G
V2



Floating gate design



$\varepsilon_b > \varepsilon_a$

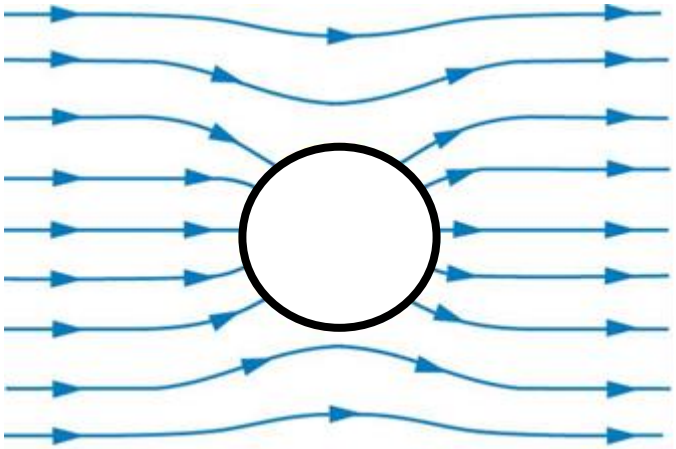


$\varepsilon_b \leq \varepsilon_a$

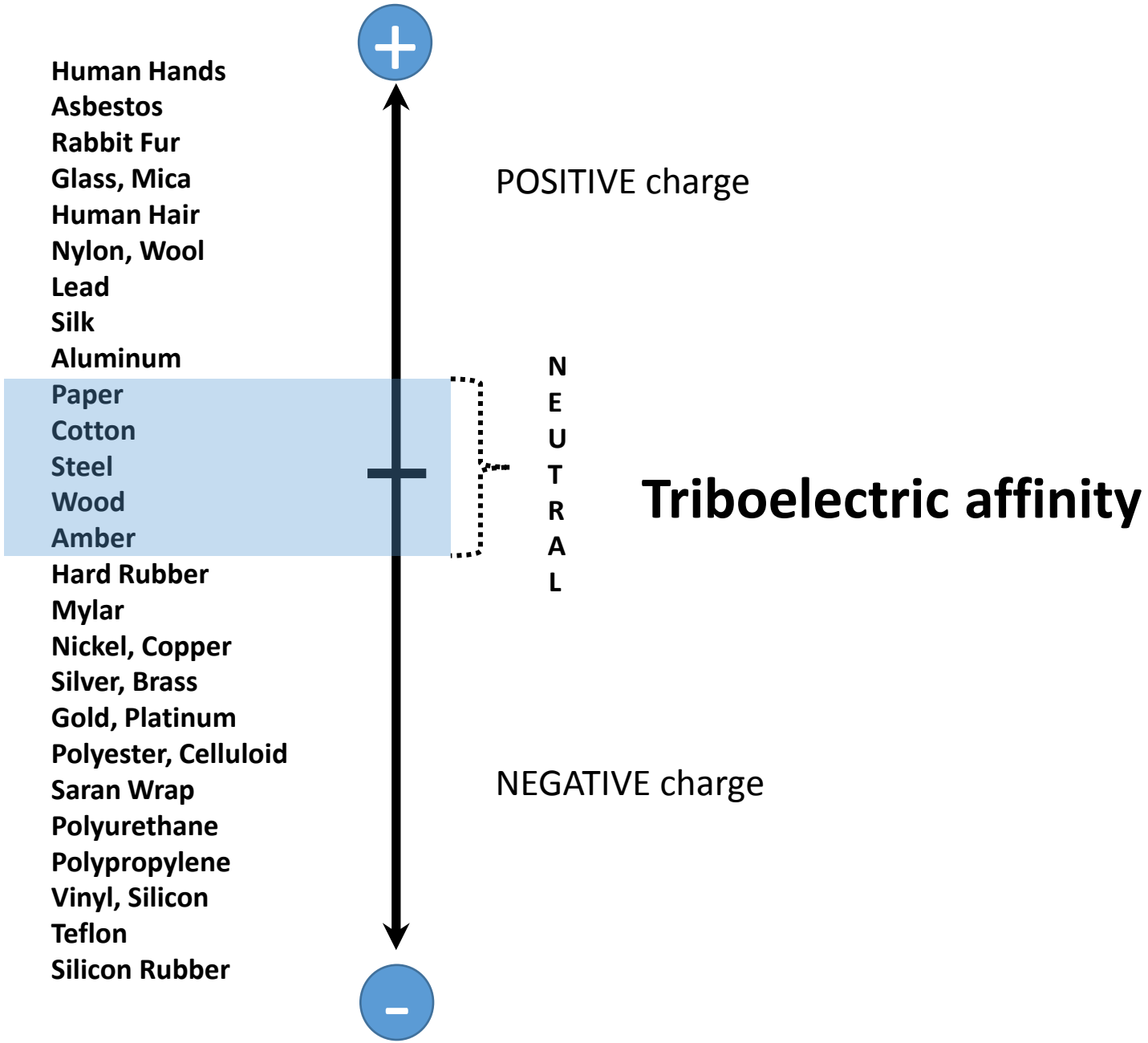
Dielectric constant, relative permittivity, ε

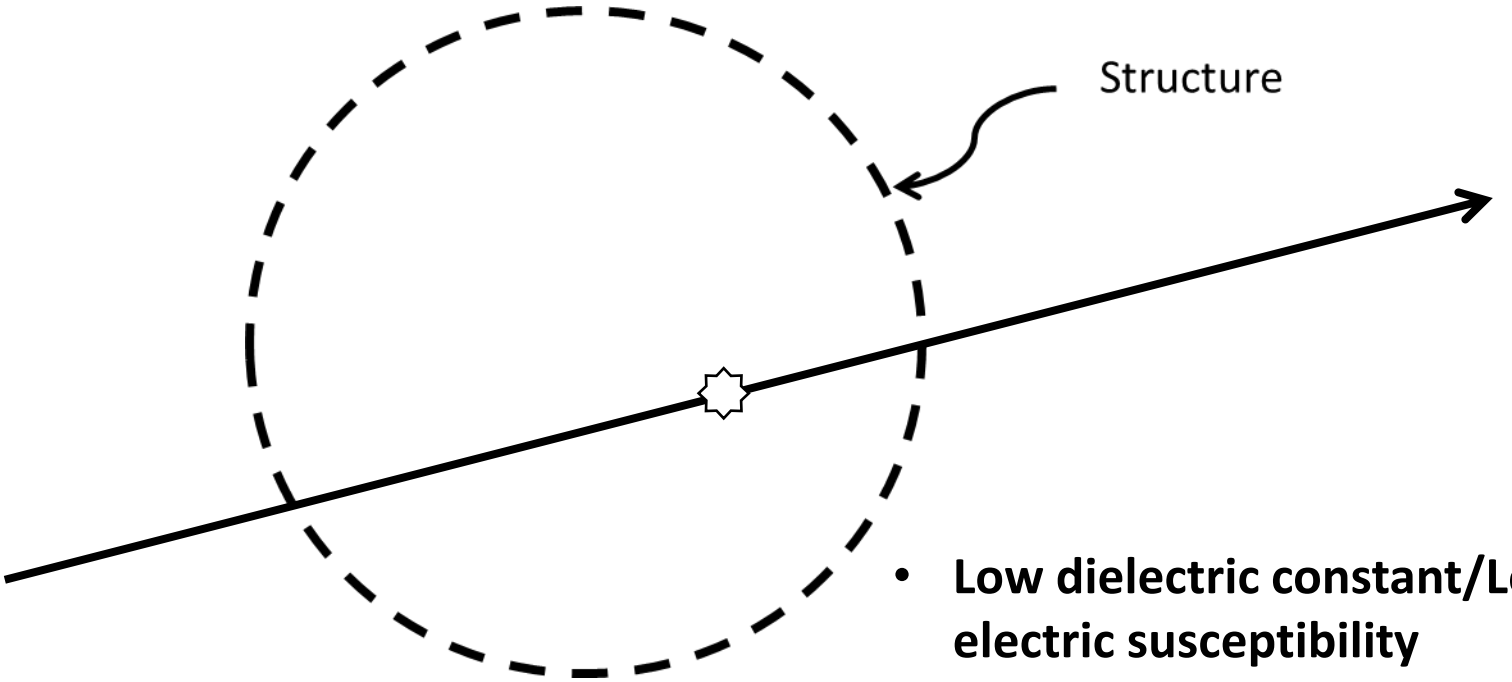
Electric susceptibility, $\chi = 1 - \varepsilon$

$\varepsilon = 1$ vacuum



Conductor


Human Hands
Asbestos
Rabbit Fur
Glass, Mica
Human Hair
Nylon, Wool
Lead
Silk
Aluminum
Paper
Cotton
Steel
Wood
Amber
Hard Rubber
Mylar
Nickel, Copper
Silver, Brass
Gold, Platinum
Polyester, Celluloid
Saran Wrap
Polyurethane
Polypropylene
Vinyl, Silicon
Teflon
Silicon Rubber
+
−
POSITIVE charge
NEUTRAL
NEGATIVE charge
Triboelectric affinity



- **Low dielectric constant/Low electric susceptibility**
- **Non-conductor**
- **Neutral triboelectric affinity**

Catch 22

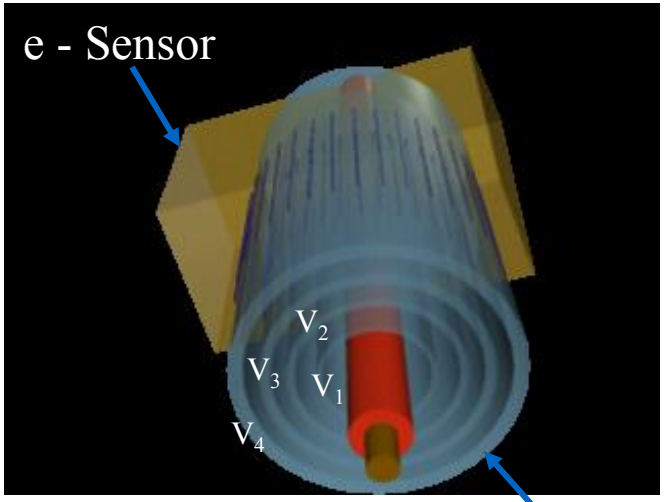
- **Want to select the best materials for constructing an electric field measurement system, however, the actual electrical properties vary or are unknown in configuration to be used.**

- **Insulation on wiring**
- **Wire diameters**
- **Circuit elements**
- **Support materials**

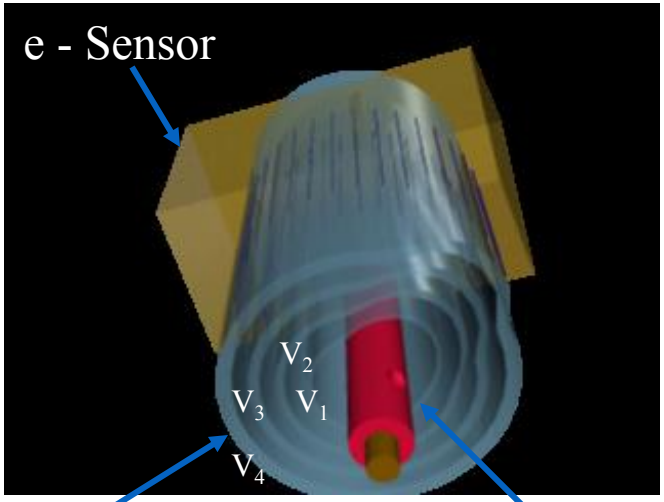
- **Don't know actual electrical properties until tested**

An Example, "e - Sensor" Antenna Configuration for Wiring Inspection

New Insulation



Damaged Insulation



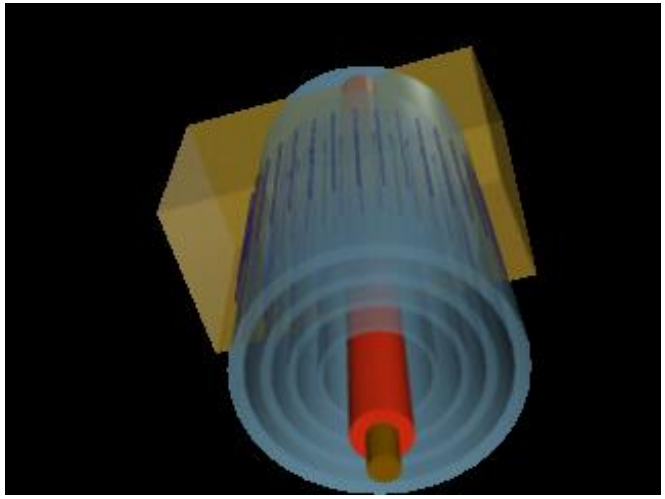
Equipotential surfaces

Damaged insulation

Electrical equipotential surfaces (V_1, V_2, V_3, V_4) are distorted due to damaged or aged insulation. Some antenna elements are no longer parallel to the electrical equipotential surfaces and now are exposed to an increase in potential.

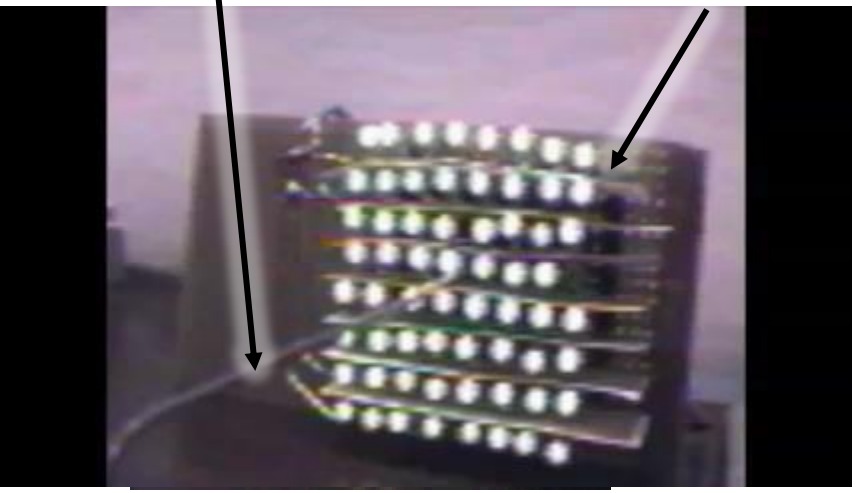
The electric field, **E,** at any point is given by $-\vec{\nabla}V = \vec{E}$, where V is the electrical potential

"e - Sensor" Data from Prototype

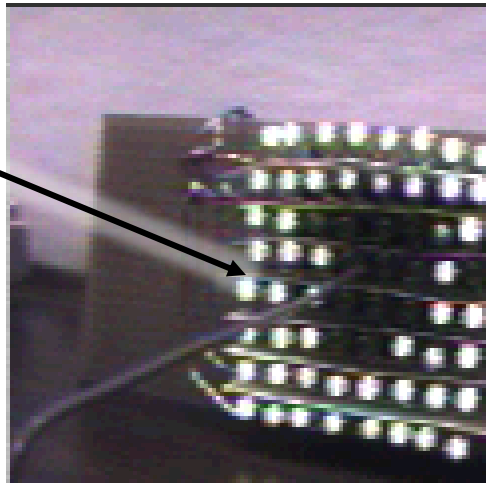


Wire passing through
e - Sensor prototype

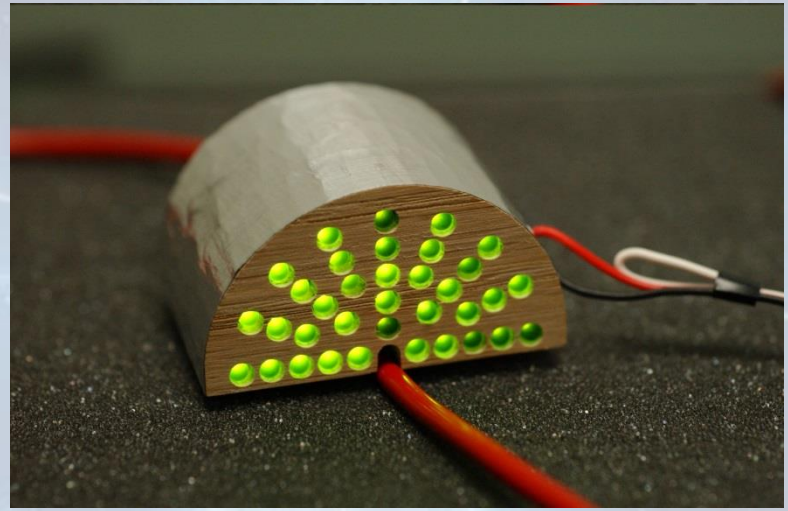
e - Sensor

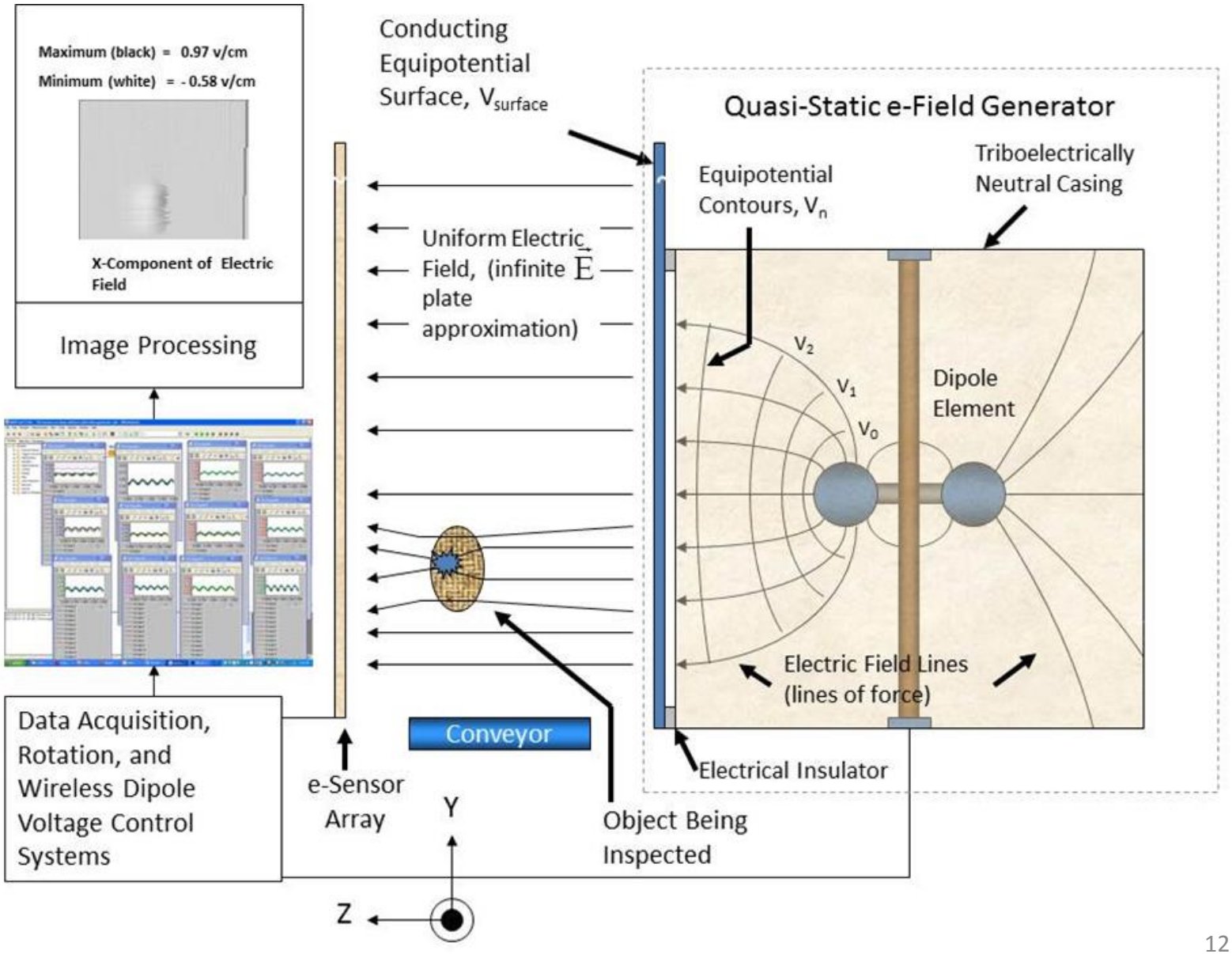


e - Sensor LEDs are dimmed proportionately by the presence of the spatially varying electric potential existing around statically charged insulated wire.



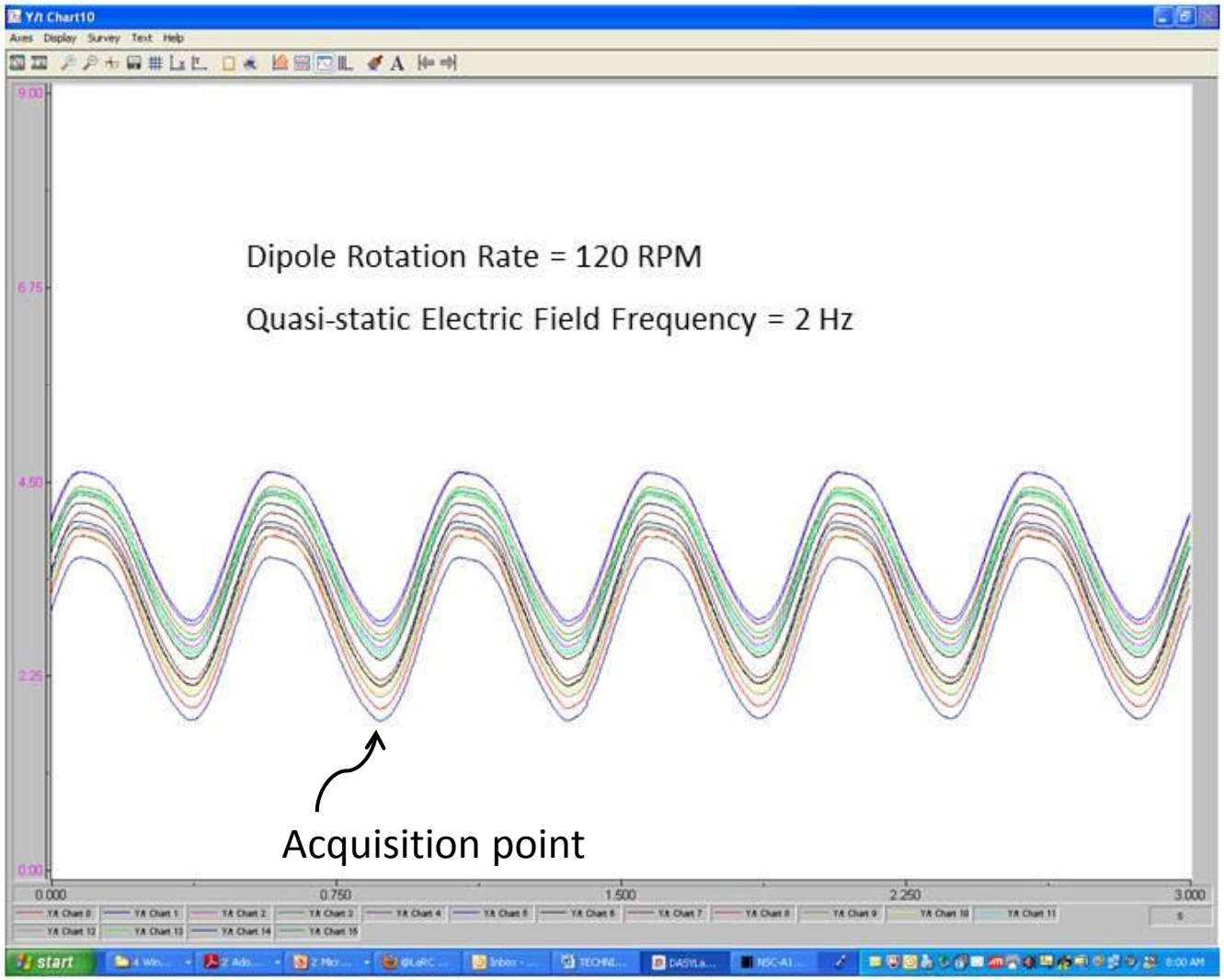
2nd Prototype




Maximum (black) = 0.97 v/cm
Minimum (white) = - 0.58 v/cm
X-Component of Electric Field
Image Processing
Conducting Equipotential Surface, $V_{surface}$
Uniform Electric Field, (infinite plate approximation) $\vec{E}$
Quasi-Static e-Field Generator
Equipotential Contours, V_n
Triboelectrically Neutral Casing
V_2
V_1
V_0
Dipole Element
Electric Field Lines (lines of force)
Electrical Insulator
Data Acquisition, Rotation, and Wireless Dipole Voltage Control Systems
e-Sensor Array
Conveyor
Object Being Inspected
Y
Z

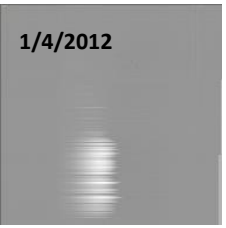

QUASI-STATIC
GENERATOR
CAUTION

Voltage Response from 16 e-Sensors



Electric Potential Image of Human

Using Electric Field Imaging (2016) US 9279719 B2 & Quasi-Static Electric Field Generator (2016) US20160049885A1



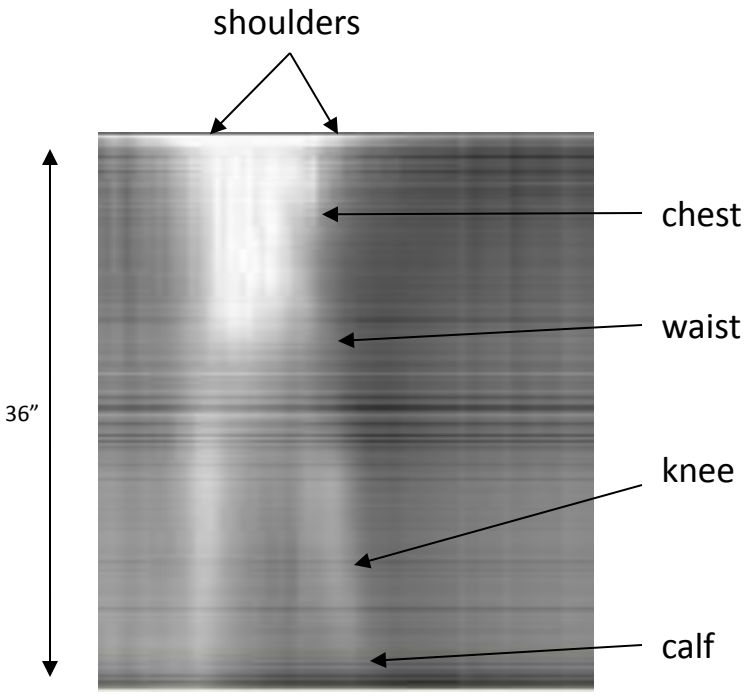


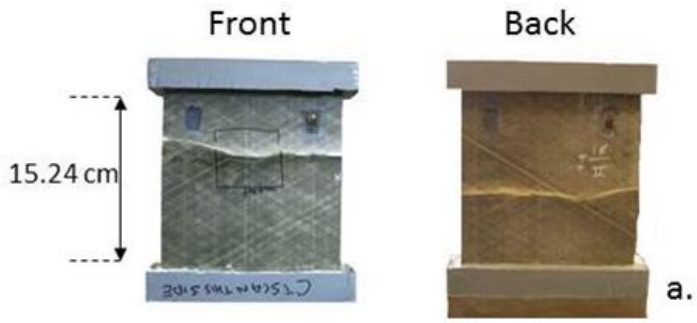
Image Processing

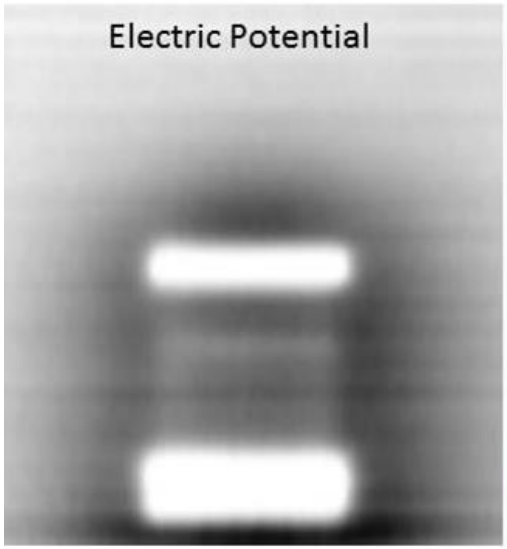
Ed Generazio’s

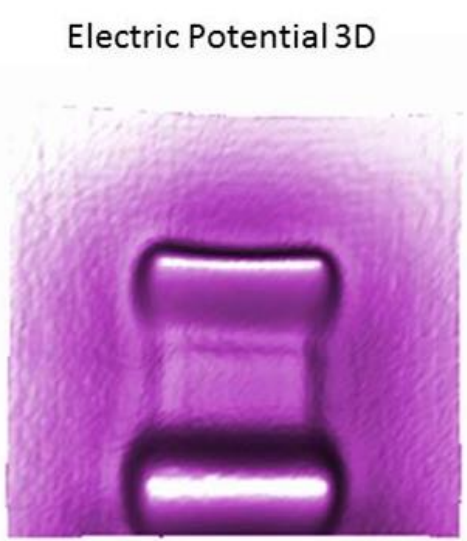
1st electric field image of a human, 10/23/2012

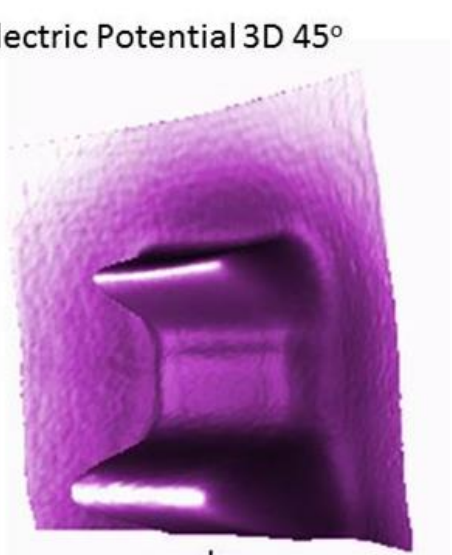
Electrical potential image of a human in a uniform electric field

- First images identify rich areas of improvement.
- Imaging volumetric dielectric properties of structures

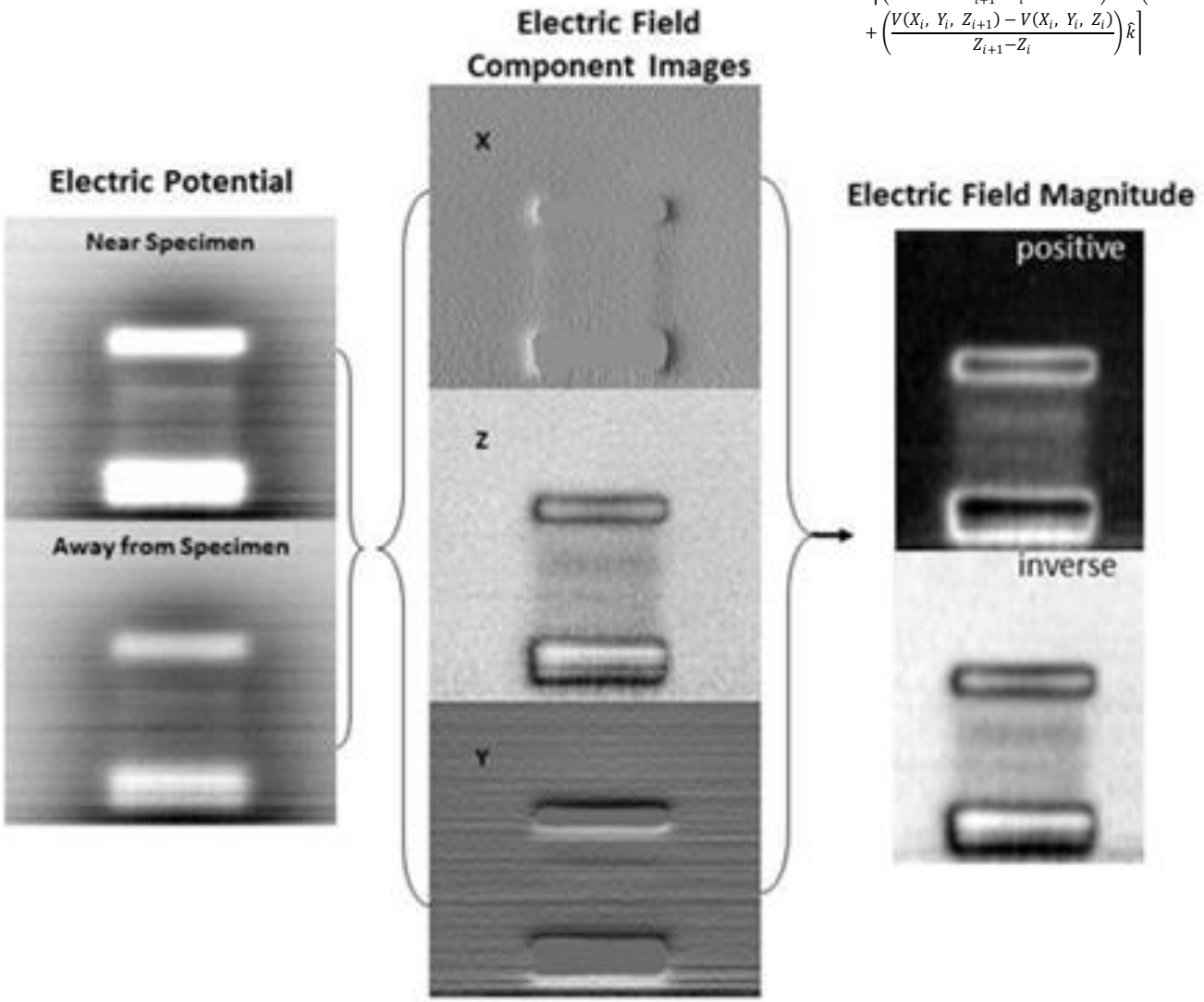

Front
Back
15.24 cm
a.


Electric Potential
b.

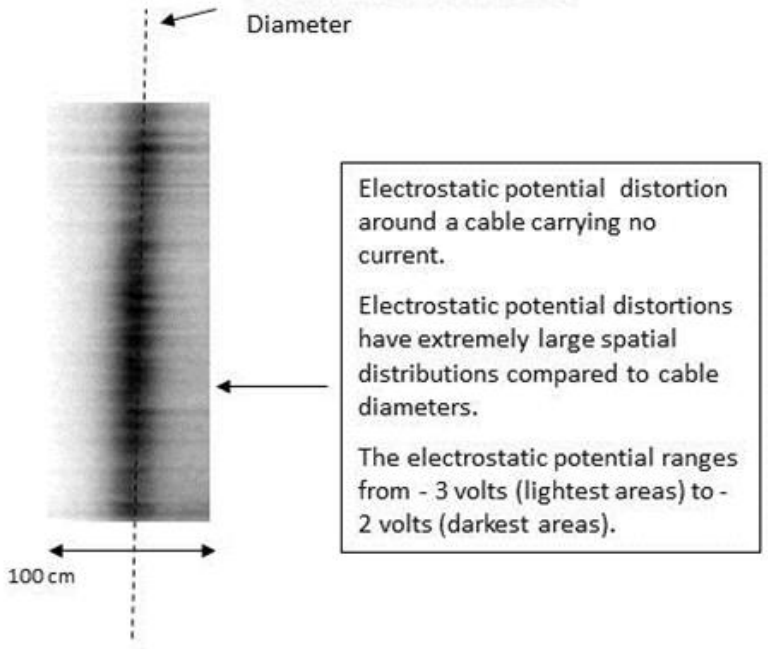

Electric Potential 3D
c.


Electric Potential 3D 45°
d.

$$\vec{E}(X_i,Y_i,Z_i) \approx -\left[\left(\frac{V(X_{i+1},\ Y_i,\ Z_i)-V(X_i,Y_i,Z_i)}{X_{i+1}-X_i}\right)\hat{\imath}+\left(\frac{V(X_i,\ Y_{i+1},\ Z_i)-V(X_i,\ Y_i,Z_i)}{Y_{i+1}-Y_i}\right)\hat{\jmath}\right.$$
$$\left.+\left(\frac{V(X_i,\ Y_i,\ Z_{i+1})-V(X_i,\ Y_i,\ Z_i)}{Z_{i+1}-Z_i}\right)\hat{k}\right]$$



Generazio, E. R., *Electric Potential and Electric Field Imaging with Applications*, Materials Evaluation, November 2015, pgs. 1479 - 1489



Electrostatic potential distortion around a cable carrying no current.

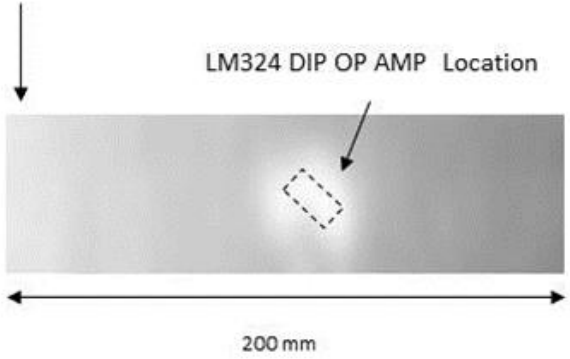
Electrostatic potential distortions have extremely large spatial distributions compared to cable diameters.

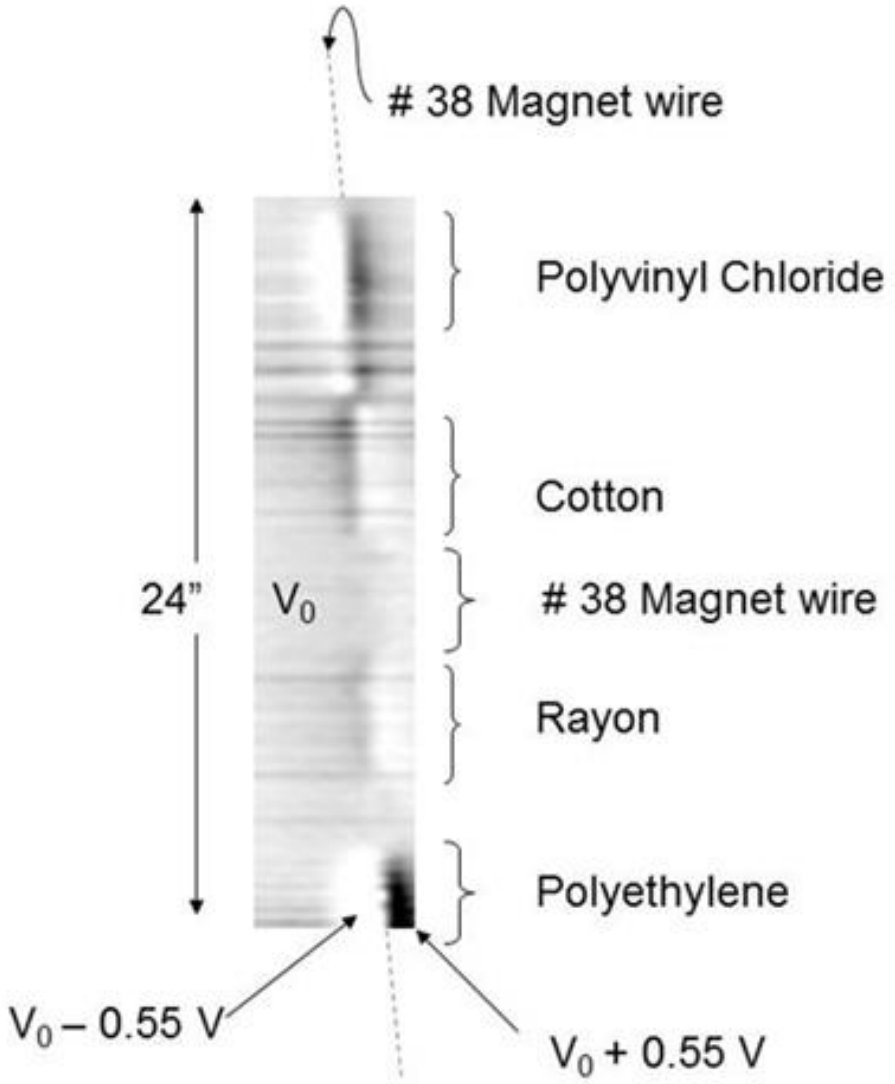
The electrostatic potential ranges from - 3 volts (lightest areas) to - 2 volts (darkest areas).

Image of actual electrostatic potential distortion around LM324 Operational Amplifier (LM324 DIP), 10 mm x 20 mm top surface is normal to reference electric field.

Electrostatic potential distortions have extremely large spatial distributions compared to amplifier dimensions.

The electrostatic potential ranges from - 3 volts (darkest areas) to - 4 volts (lightest areas).

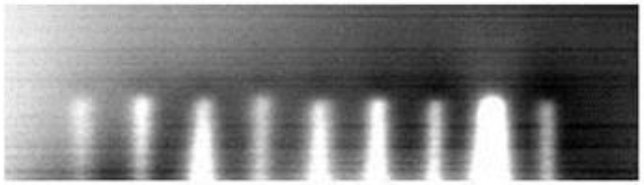




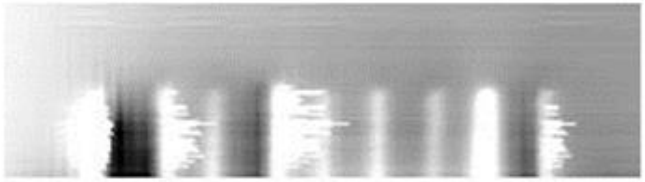
Electric Potential Image

Electric Potential Images

As received rods



60.96 cm

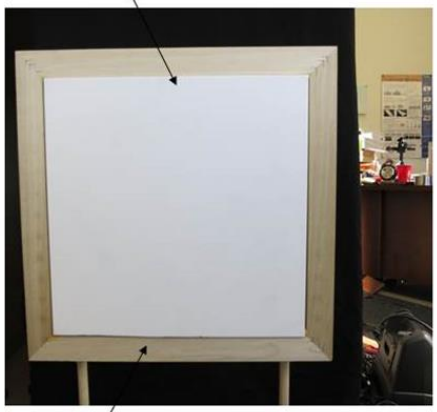


Silk cloth passed over surface

Dielectric Constant ε		Triboelectric Affinity
2.0 – 2.1	PTFE	-190
2.7	Acrylic	-10
1.2 – 2.1	Wood	+7
3	Nylon	+30
5 – 5	Garolite	+30
4 - 9	Mica ceramic	
3.8	Borosilicate Glass	+25
	Copper	~0
2.8 - 4.1	Polyester	-40

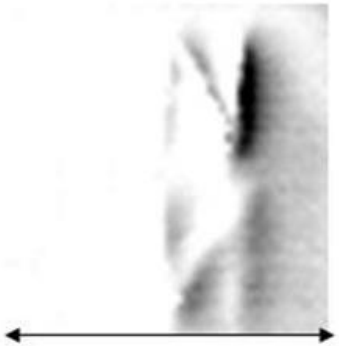
Samples are in order left to right

EFI: New Electrostatic Eyes



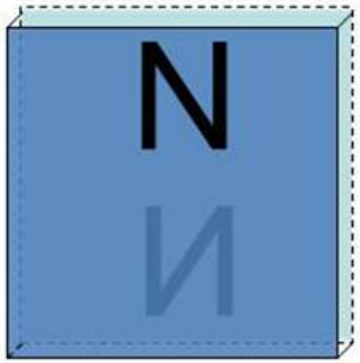
EFI Electrostatic Potential Image of latent charge distribution generated by triboelectrically drawing the letters "NASA" on PTFE. The EFI image is ovelaid onto the area scanned.

Electric Potential Image



PTFE, Teflon Panel

6.35 mm x 30.38 cm x 30.38 cm



The letter "N" triboelectrically hand drawn on the front (upper) and back (lower) of a PTFE panel.

Characterization by Charge Tunneling, Injection, and Distribution

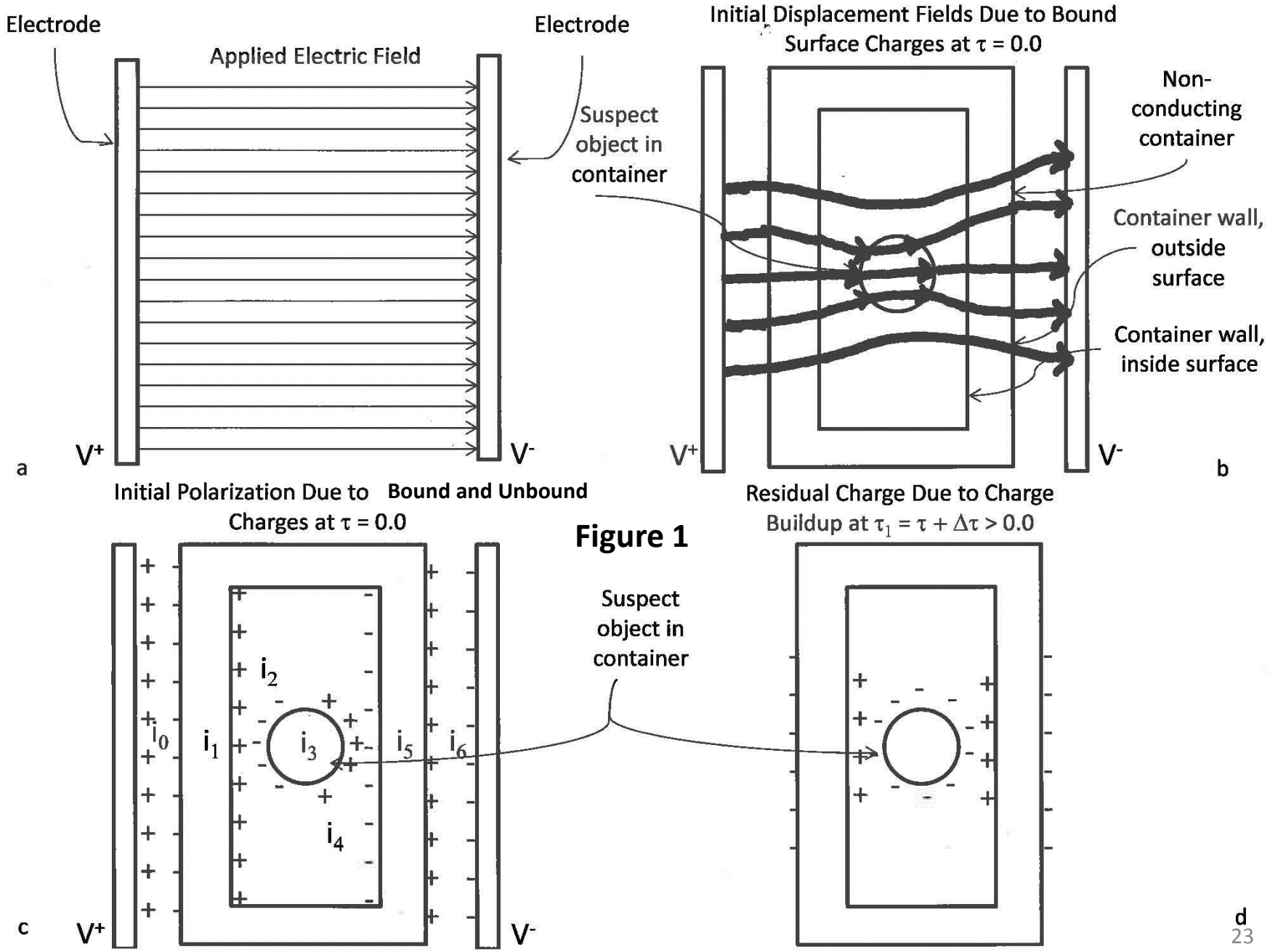
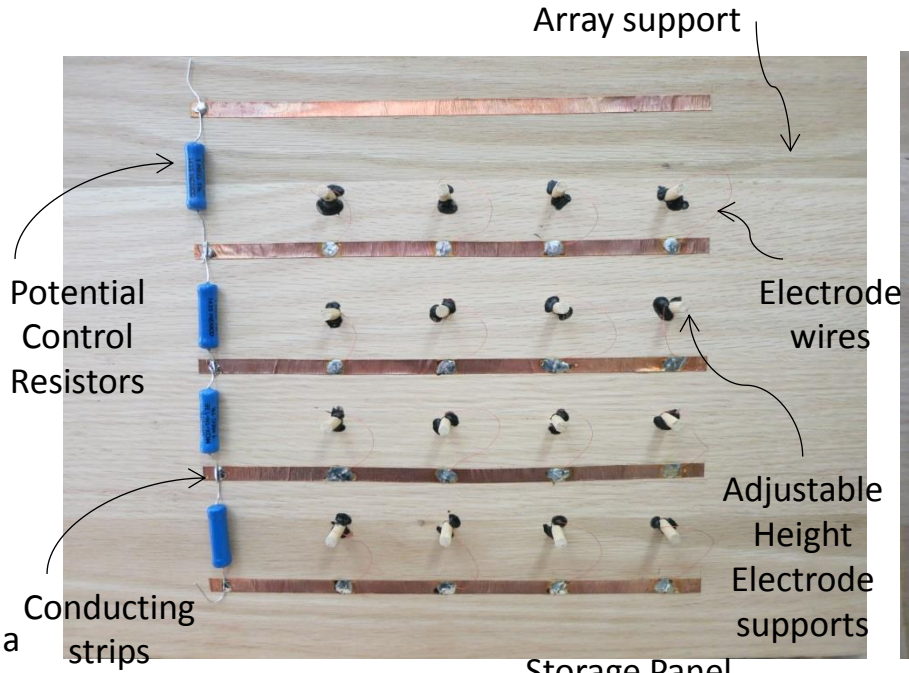
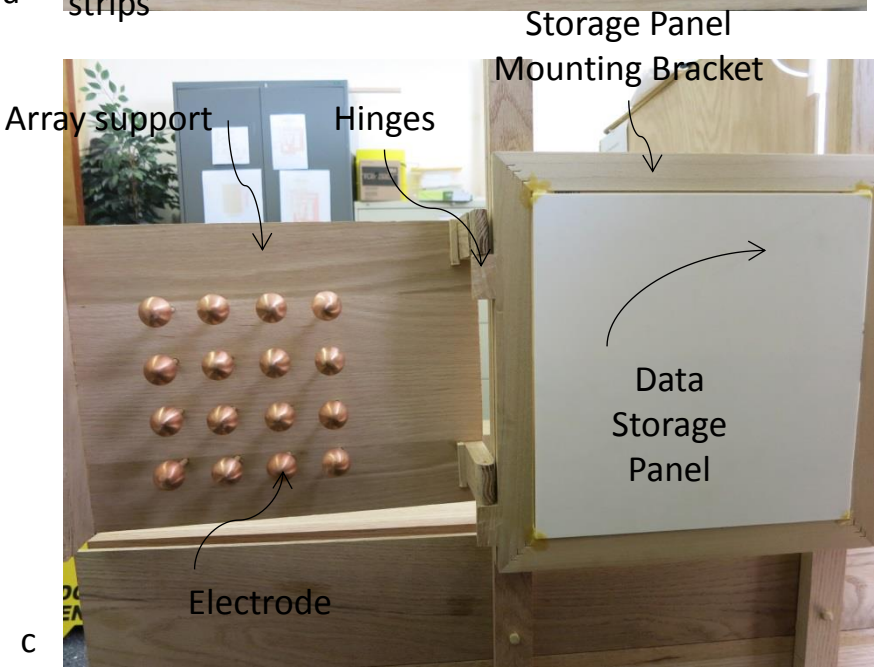
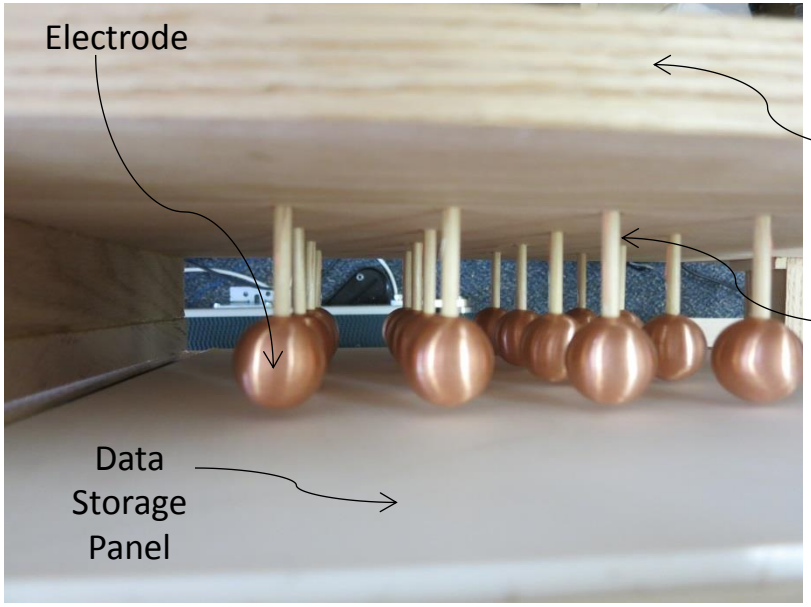

Electrode
Applied Electric Field
Electrode
Suspect object in container
V+
V-
a
Initial Displacement Fields Due to Bound Surface Charges at τ = 0.0
Non-conducting container
Container wall, outside surface
Container wall, inside surface
V+
V-
b
Initial Polarization Due to Bound and Unbound Charges at τ = 0.0
i0
i1
i2
i3
i4
i5
i6
V+
V-
c
Residual Charge Due to Charge Buildup at τ1 = τ + Δτ > 0.0
Suspect object in container
d

Figure 1

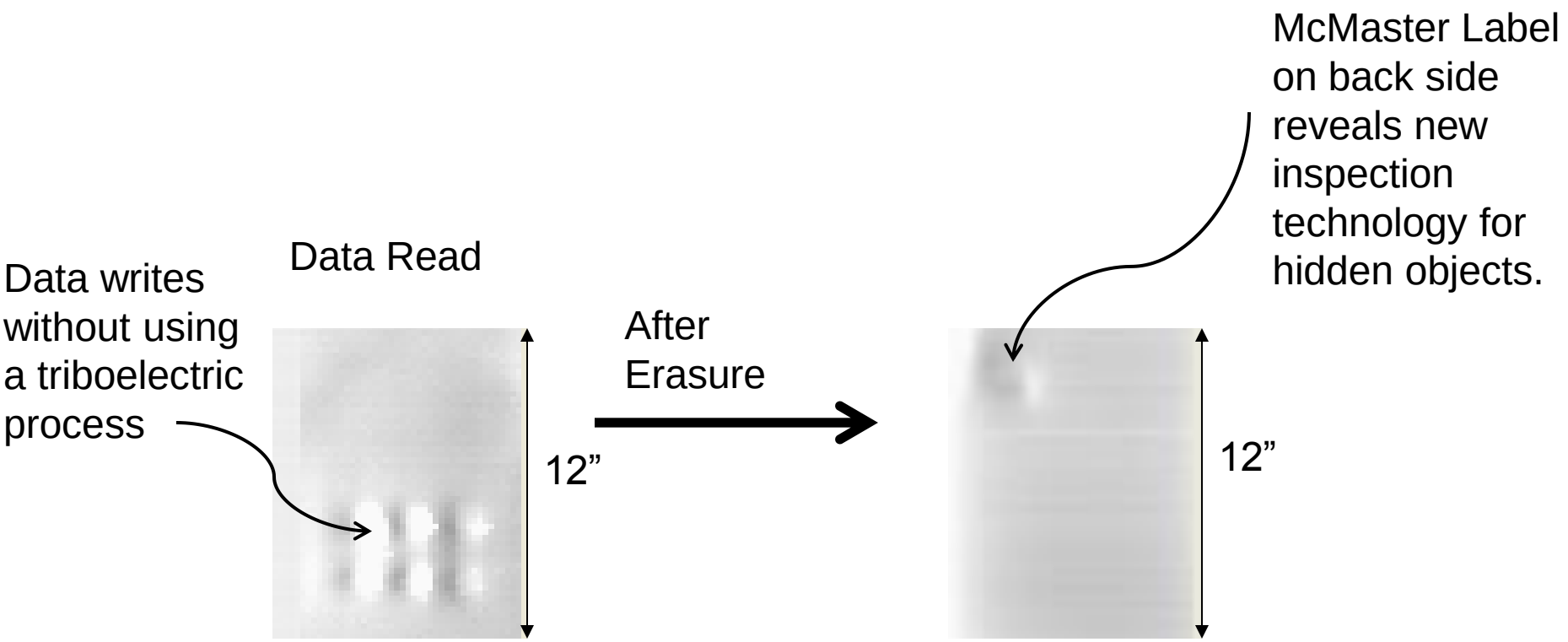
e-Sensor data write test bed system – identifying organic memory parameters





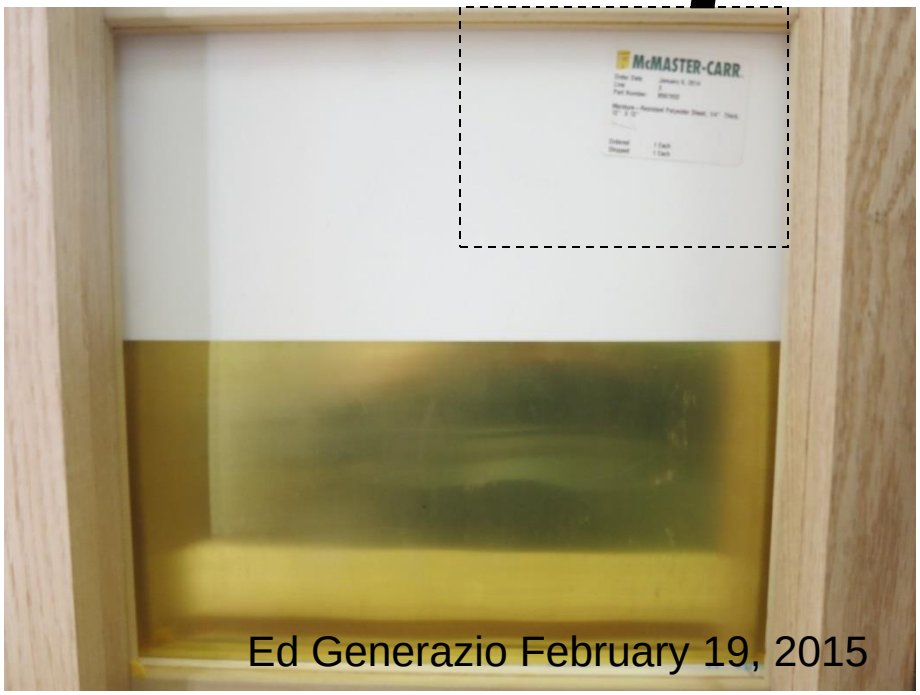


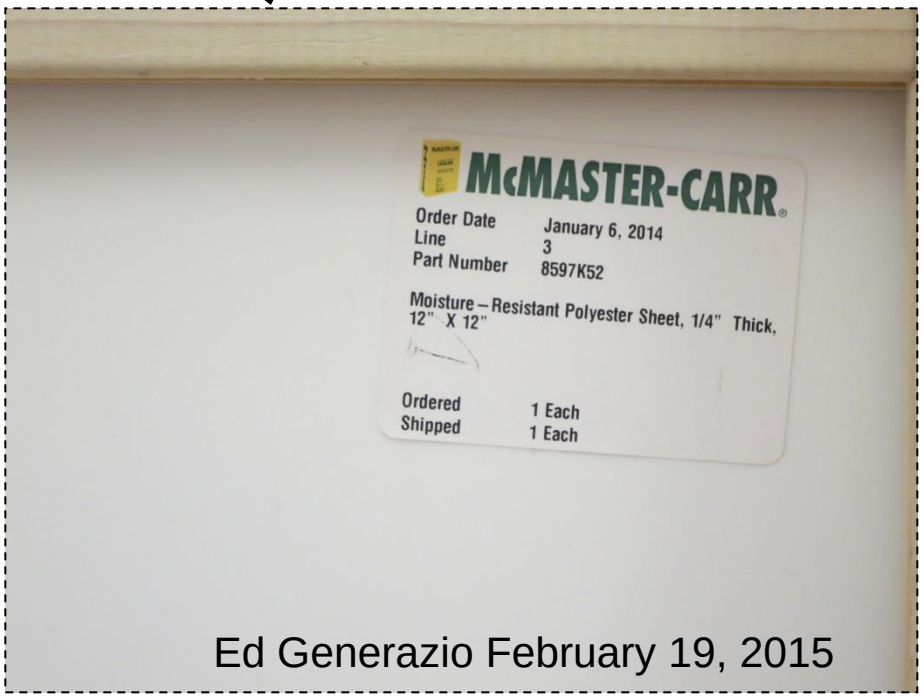
EFI image of Electrical Potential of Data Stored by Charge Distribution on PTFE



Electric Potential Images

Back side of data storage panel

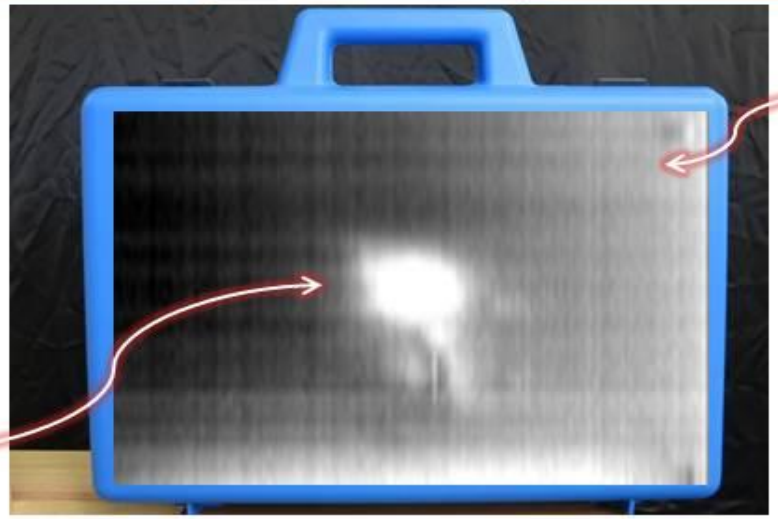




Optical image of container

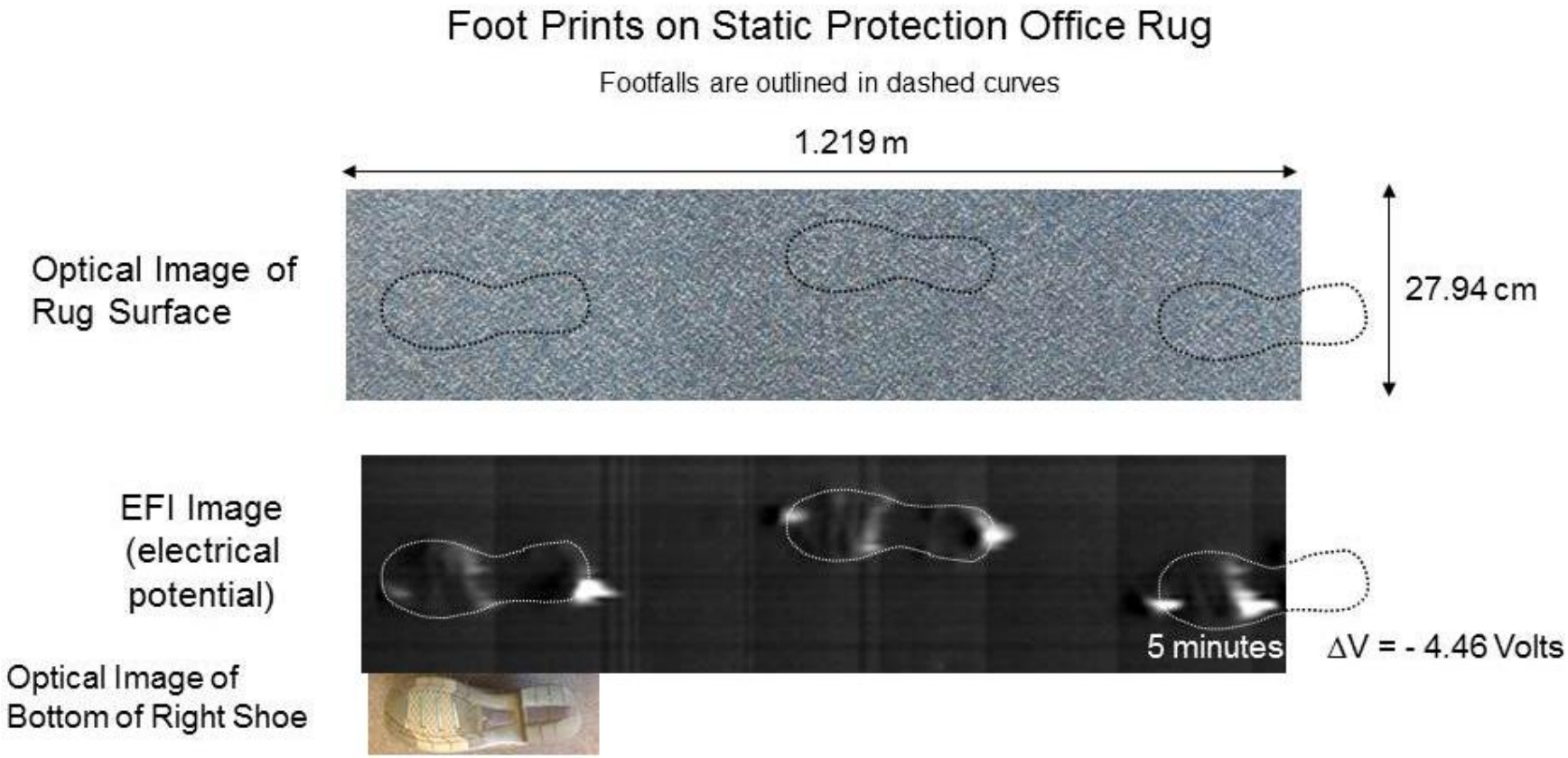
container

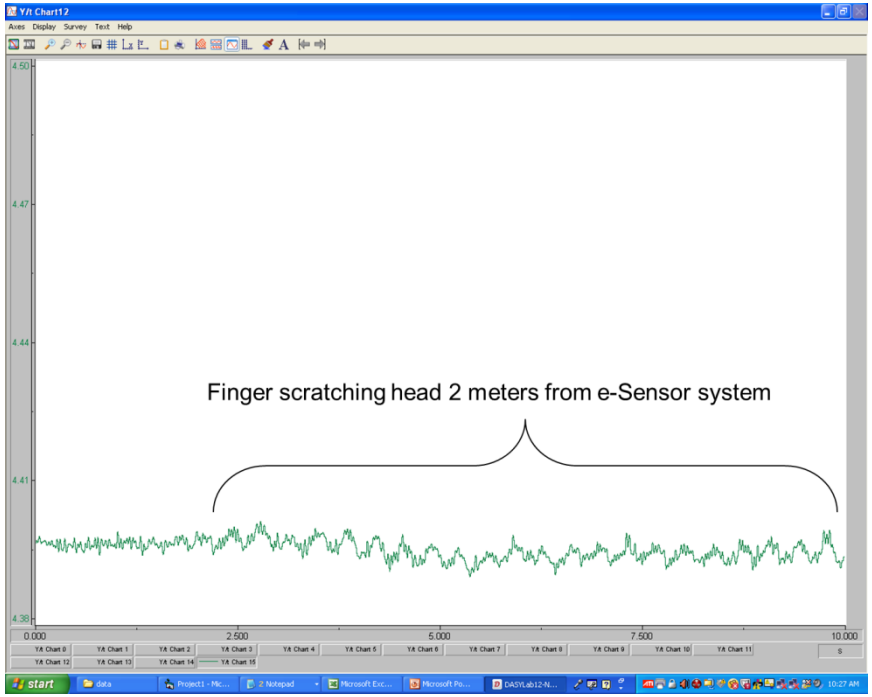
Optical image of ABS gun in container

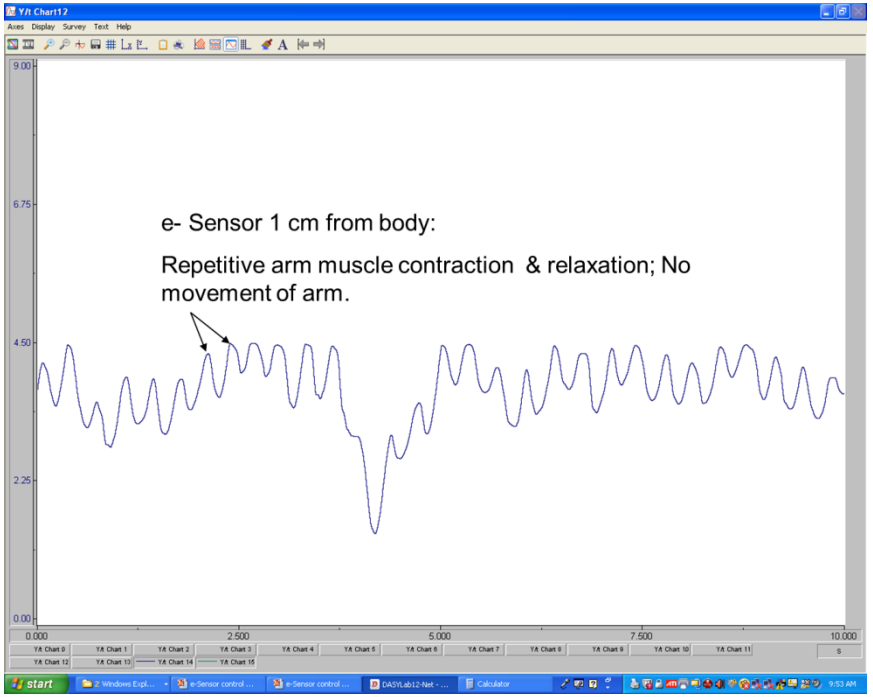


Electric potential image of container

Electric potential of gun


Foot Prints on Static Protection Office Rug
Footfalls are outlined in dashed curves
1.219 m
Optical Image of Rug Surface
27.94 cm
EFI Image (electrical potential)
5 minutes
ΔV = - 4.46 Volts
Optical Image of Bottom of Right Shoe





Very conservative sensitivity at 1.55mV/cm

Several orders of magnitude by FET selection, components, filtering, structural design, etc.

Ephemeral e-Sensor

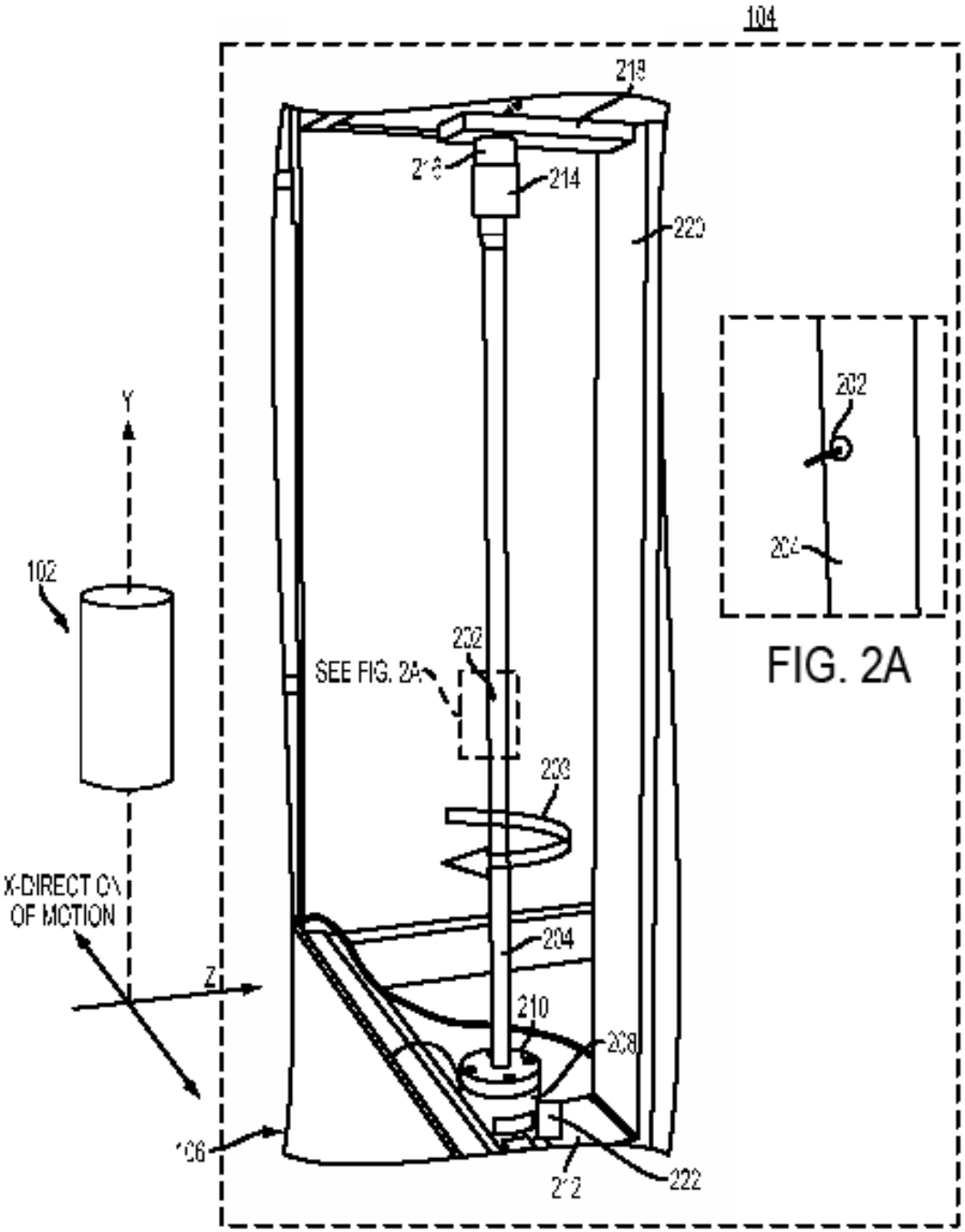
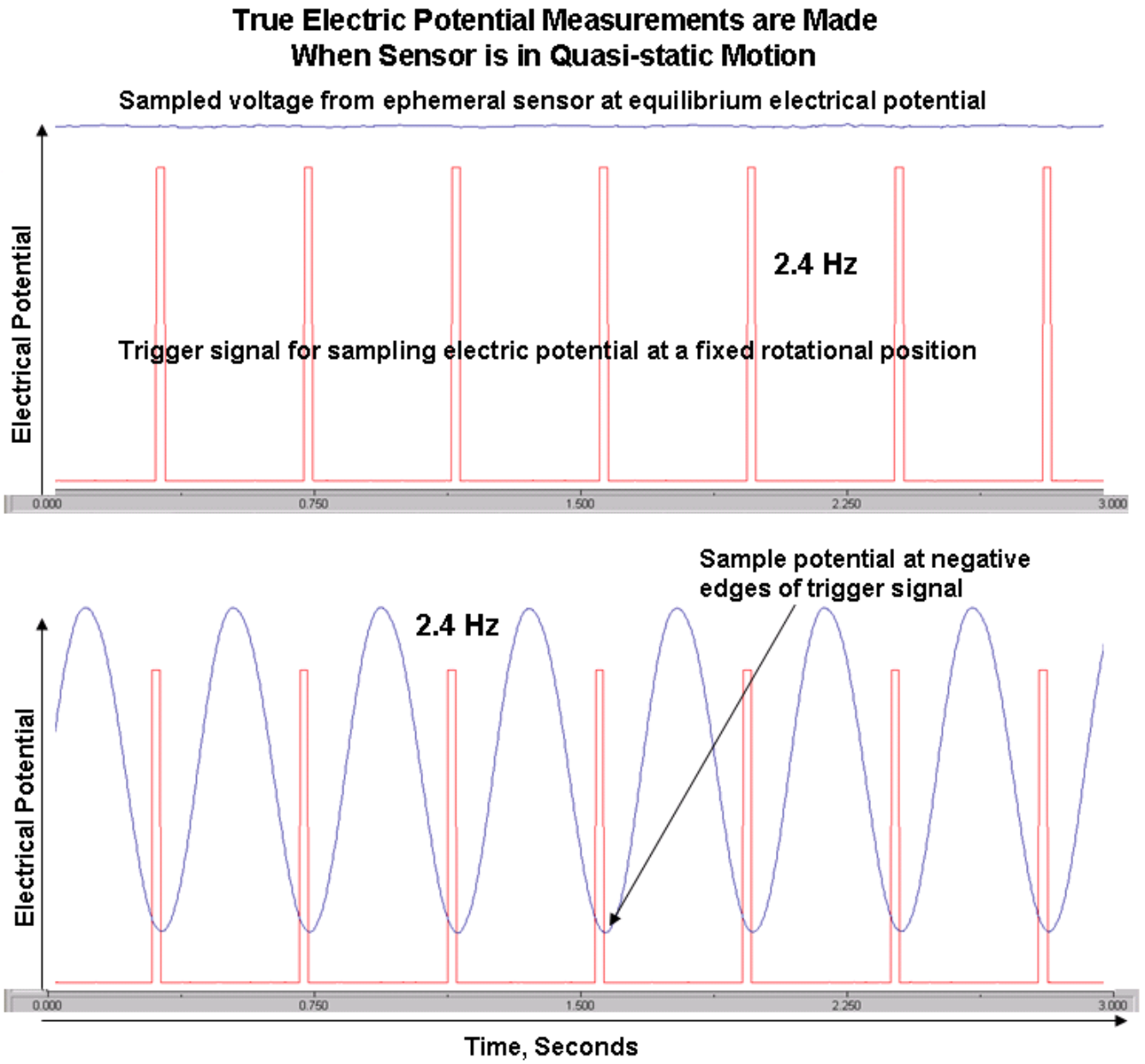
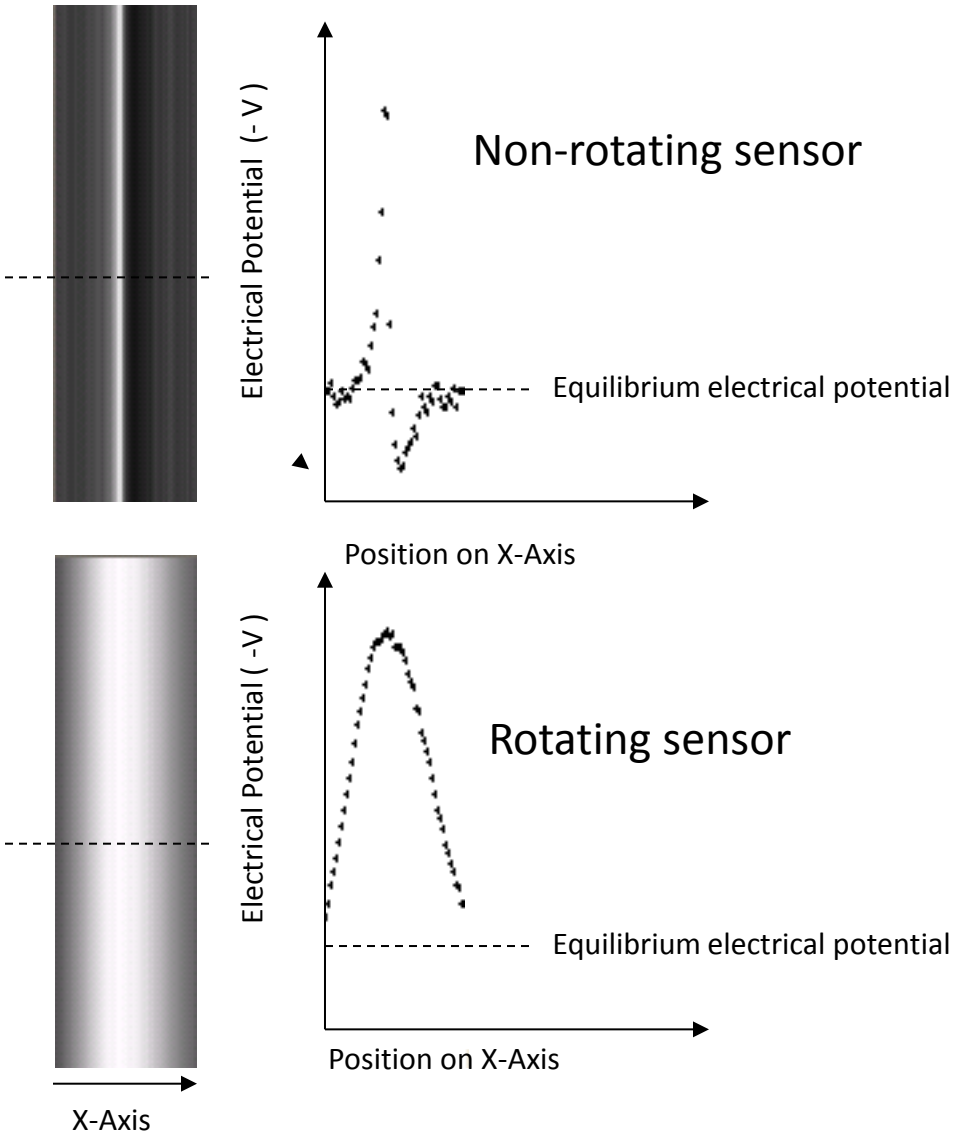

104
214
220
202
SEE FIG. 2A
206
204
210
208
222
102
Y
Z
X-DIRECTION OF MOTION

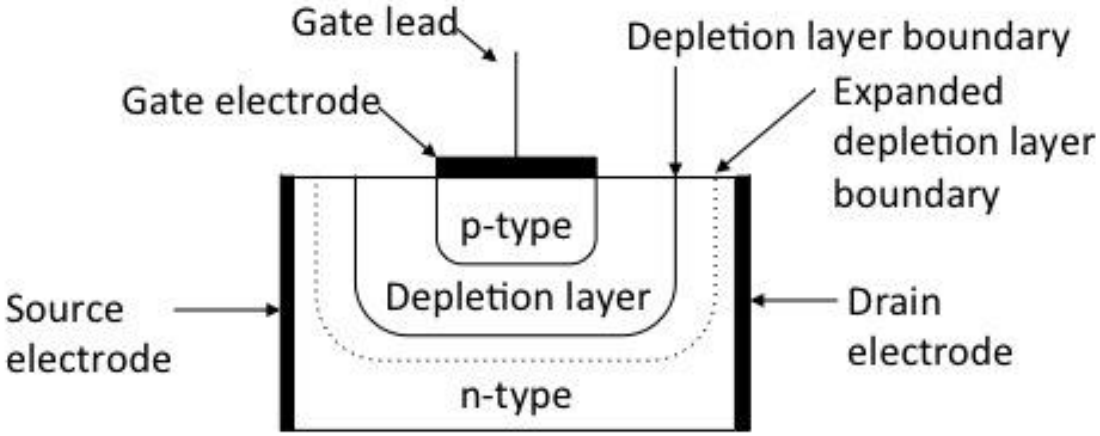
FIG. 2A

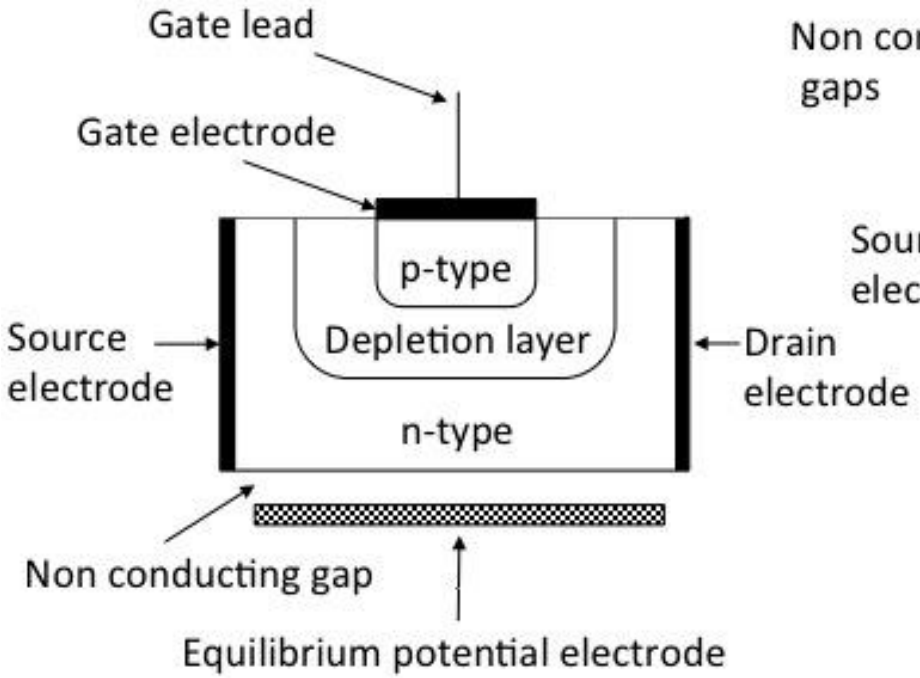

True Electric Potential Measurements are Made
When Sensor is in Quasi-static Motion
Sampled voltage from ephemeral sensor at equilibrium electrical potential
Electrical Potential
2.4 Hz
Trigger signal for sampling electric potential at a fixed rotational position
0.000
0.750
1.500
2.250
3.000
Sample potential at negative
edges of trigger signal
2.4 Hz
Electrical Potential
0.000
0.750
1.500
2.250
3.000
Time, Seconds

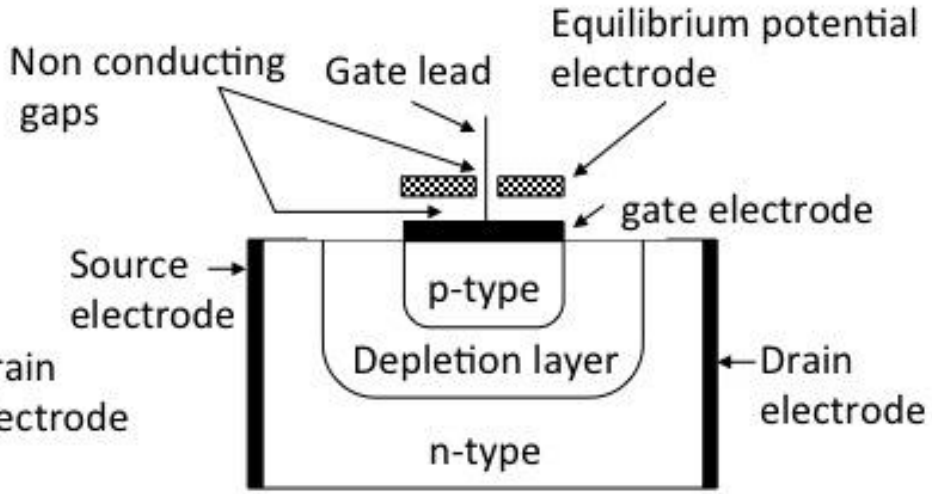
Typical Measured Ephemeral Sensor Response in the Presence of a Charged Axially Symmetric Object



Solid State
Ephemeral e-Sensor


Gate lead
Depletion layer boundary
Gate electrode
Expanded
depletion layer
boundary
p-type
Depletion layer
Source
electrode
Drain
electrode
n-type


Gate lead
Gate electrode
p-type
Source
electrode
Depletion layer
Drain
electrode
n-type
Non conducting gap
Equilibrium potential electrode


Non conducting
gaps
Gate lead
Equilibrium potential
electrode
gate electrode
Source
electrode
p-type
Depletion layer
Drain
electrode
n-type

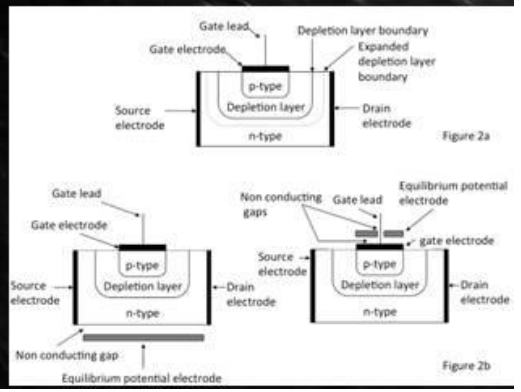
Solid State Ephemeral Sensor, ergFET

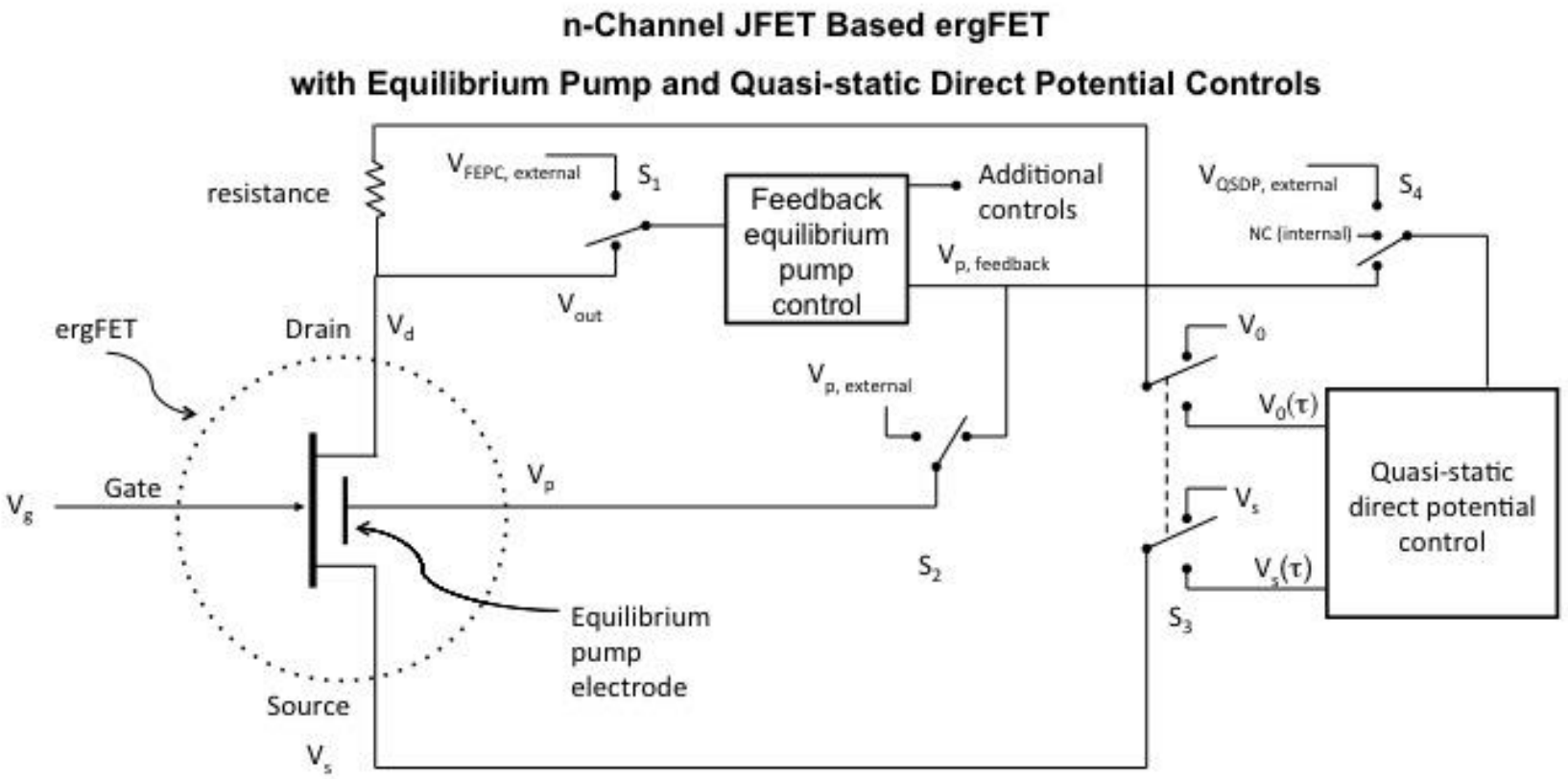
Equilibrium Pump

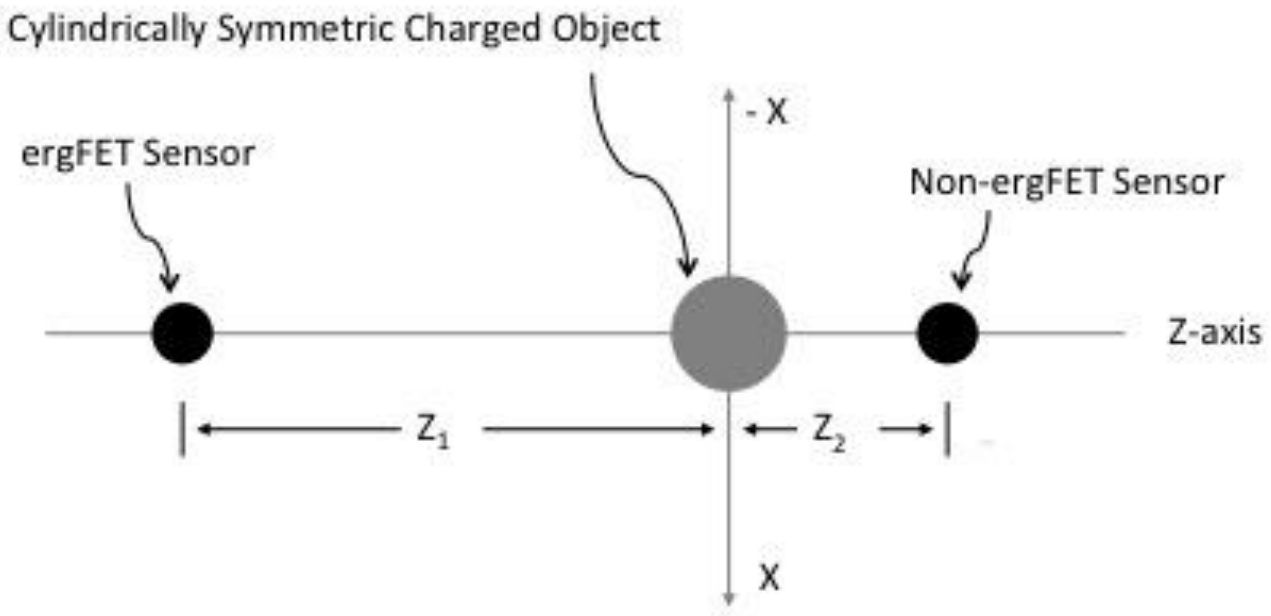
Drain

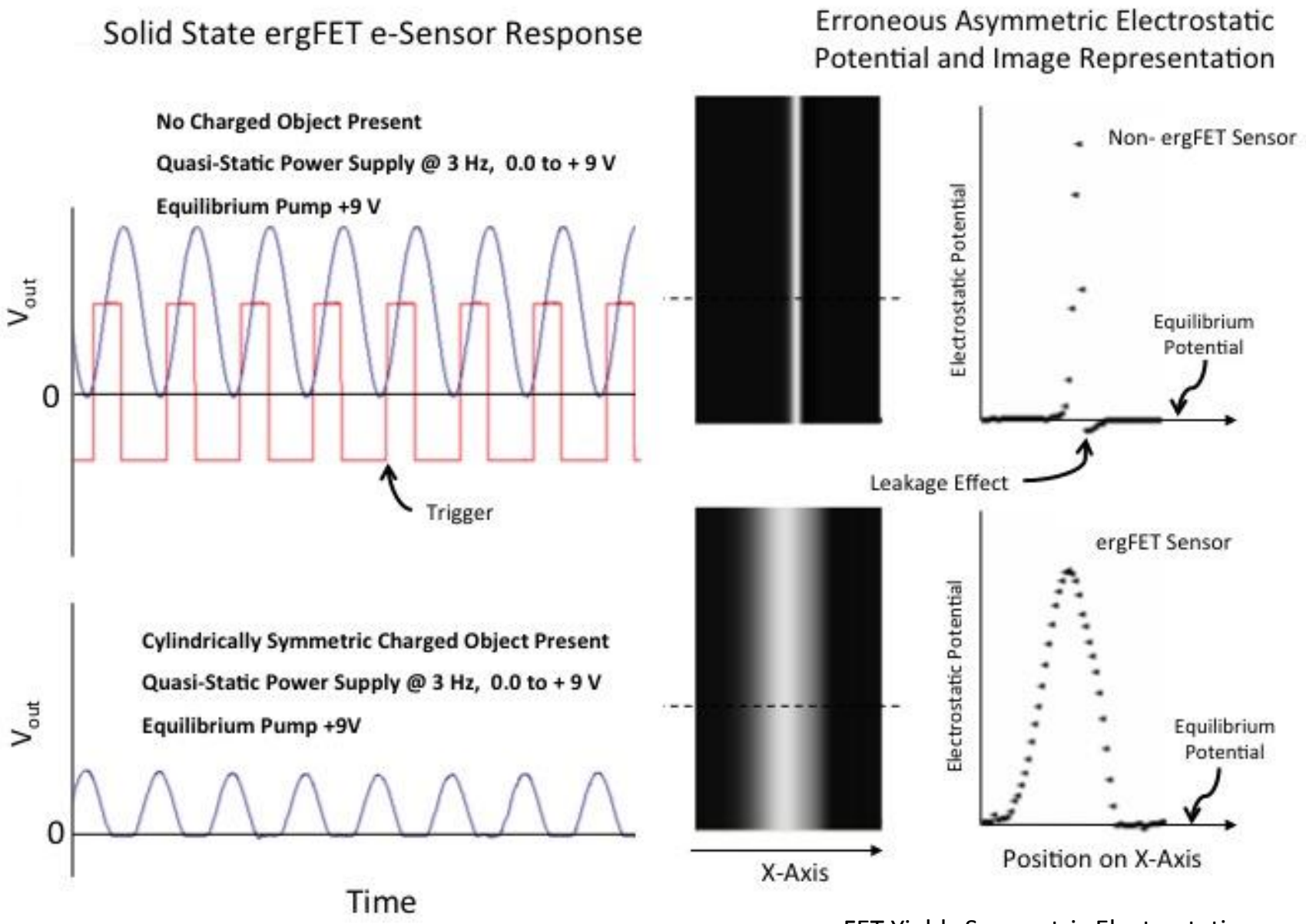
Source

Gate

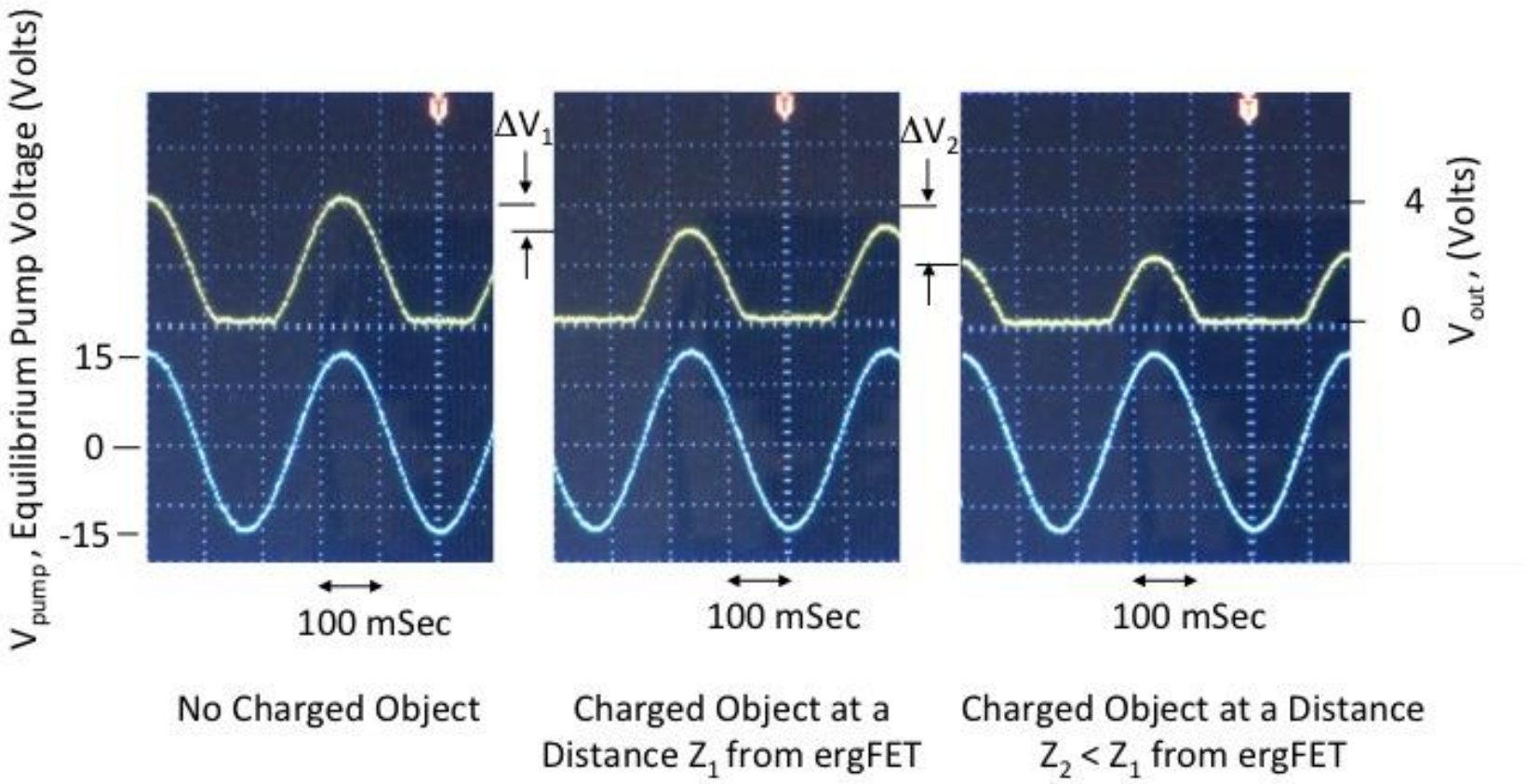



n-Channel JFET Based ergFET
with Equilibrium Pump and Quasi-static Direct Potential Controls
resistance
$V_{FEPC, external}$
S_1
Feedback equilibrium pump control
Additional controls
$V_{QSDP, external}$
S_4
NC (internal)
$V_{p, feedback}$
V_{out}
ergFET
Drain
V_d
V_0
$V_{p, external}$
$V_0(\tau)$
Quasi-static direct potential control
V_p
V_g
Gate
V_s
S_2
$V_s(\tau)$
S_3
Equilibrium pump electrode
Source
V_s


Cylindrically Symmetric Charged Object
- X
ergFET Sensor
Non-ergFET Sensor
Z-axis
Z_1
Z_2
X



ergFET Yields Symmetric Electrostatic Potential and Image Representation


V_{pump}, Equilibrium Pump Voltage (Volts)
15
0
-15
ΔV_1
ΔV_2
4
0
V_{out}, (Volts)
100 mSec
100 mSec
100 mSec
No Charged Object
Charged Object at a Distance Z_1 from ergFET
Charged Object at a Distance $Z_2 < Z_1$ from ergFET

ergFET Electrical Potential Measurements of a Single Tribo-electrically Drawn Line on Polymer Sheet

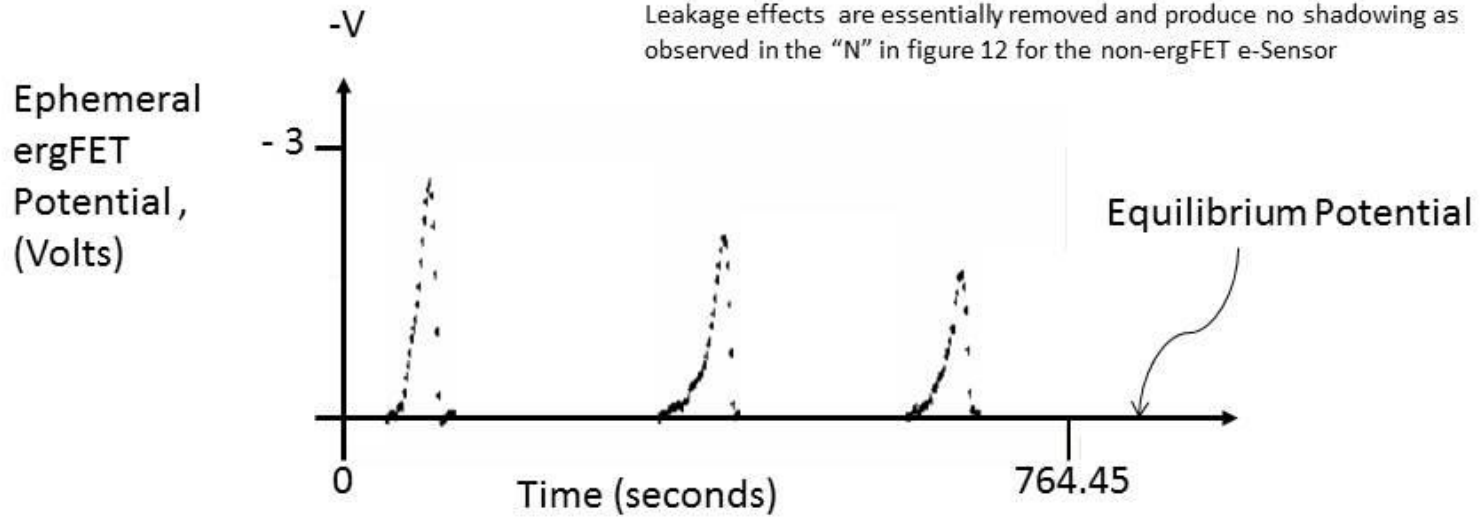
0.333 cm/sec scan speed

Quasi-static power supply at +3V to +9V @ 3 Hz;

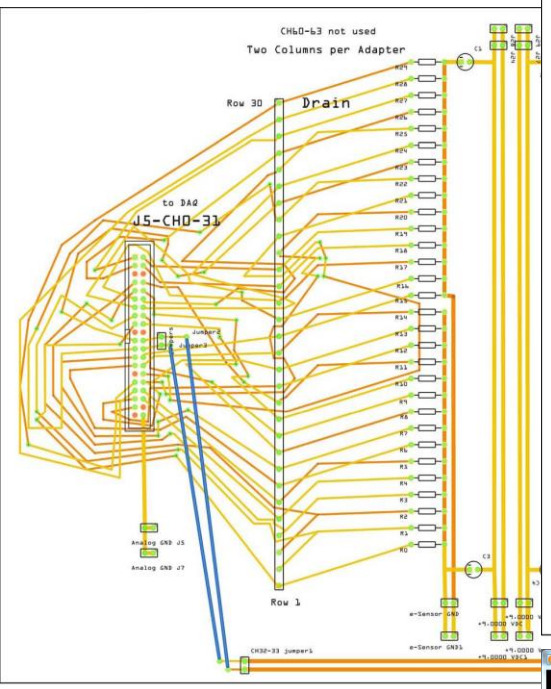
Ephemeral pump electrode at +9V

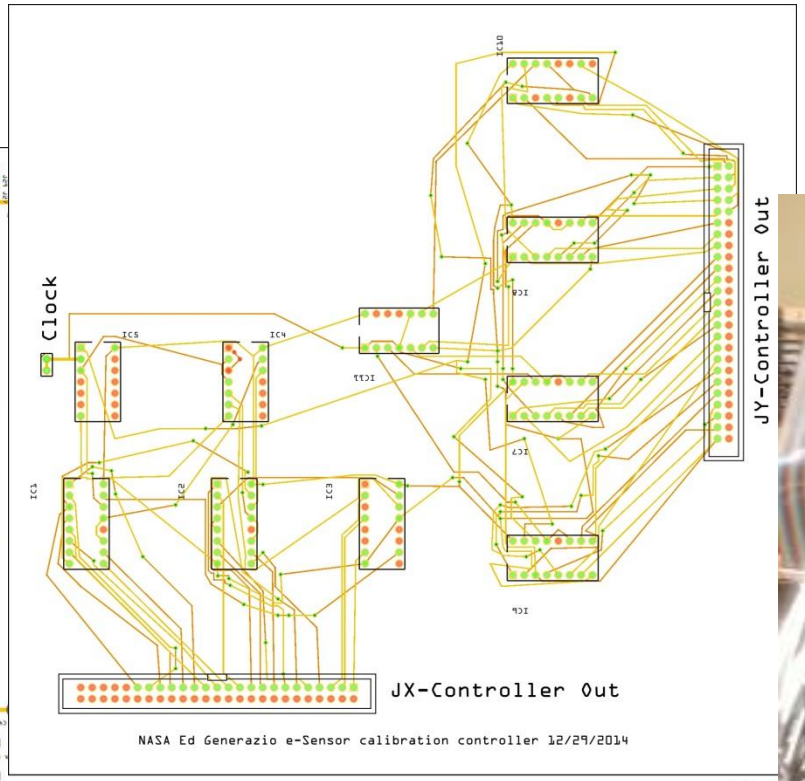
ergFET gate electrode is 3 cm from test object; compare to 3 mm for non-ergFET e-Sensor

Leakage effects are essentially removed and produce no shadowing as observed in the "N" in figure 12 for the non-ergFET e-Sensor

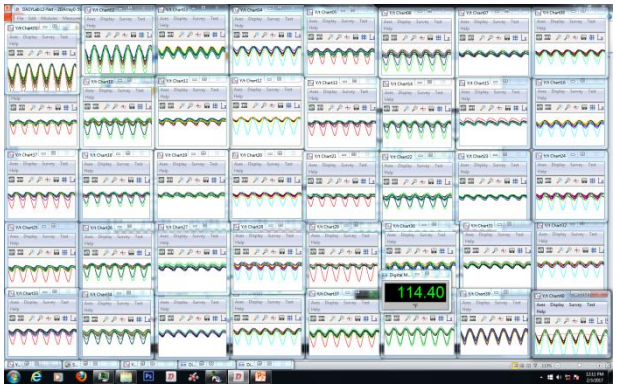


2D EFI


CH60-63 not used
Two Columns per Adapter
Row 30
Drain
to DAQ
J5-CH0-31
Row 1


Clock
JY-Controller Out
JX-Controller Out
NASA Ed Generazio e-Sensor calibration controller 12/29/2014


MVI_0004
e-Sensor Unleashed
the movie
2016


114.40


NO PHOTOGRAPHY
MULTIPLE SYSTEMS IN PATENT
TESTING, DISCLOSURE, & APPLICATIONS
QUASI-STATIC
100.24
SAMSUNG

Demonstration Test Set Up

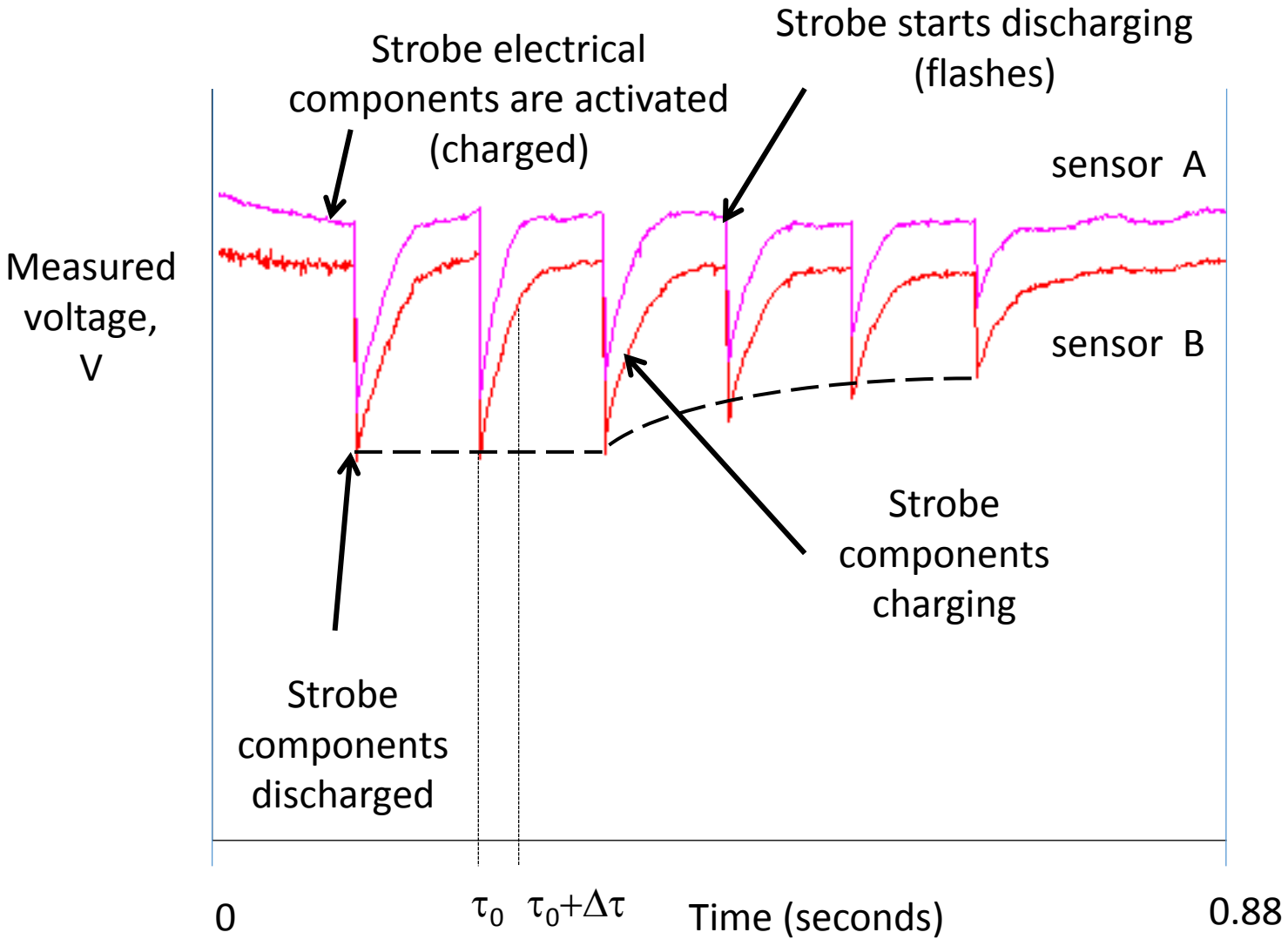
Object of interest is a circuit inside an optical flash strobe

Polymer container

Sensor array cover

Sensor array

Individual element sensor responses due to changes in strobe circuit electrical potentials



2D e-Sensor Electrical Potential Image of Activated Strobe Circuit in a Container

lightest shade represents a voltage drop of $\Delta V = -0.224$ volts

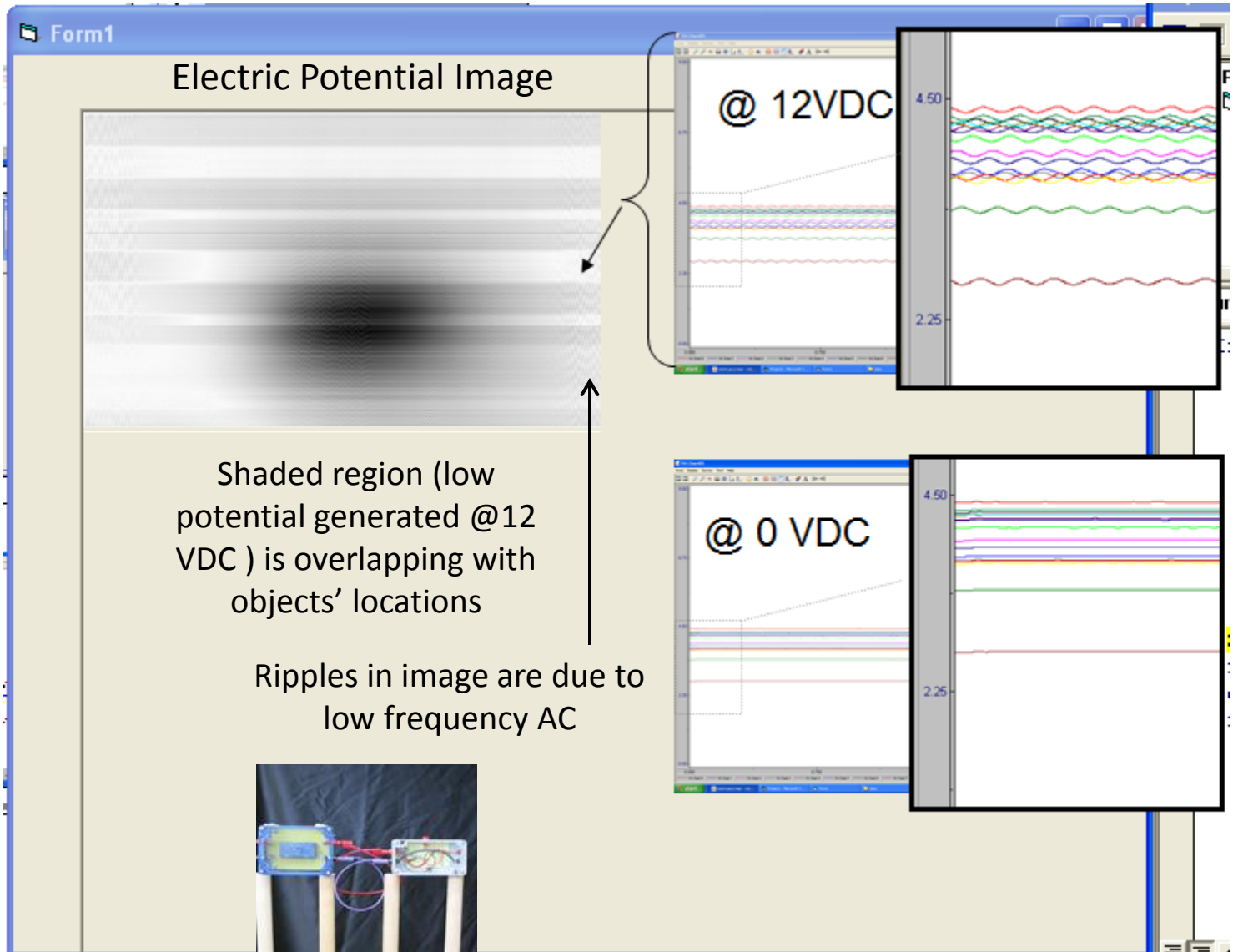
τ_0

$\tau_0 + 0.06\,\text{sec}$

e-Sensor Linear Array Scan - Electrical Potential Image

~ 26 Hz AC waveforms observed

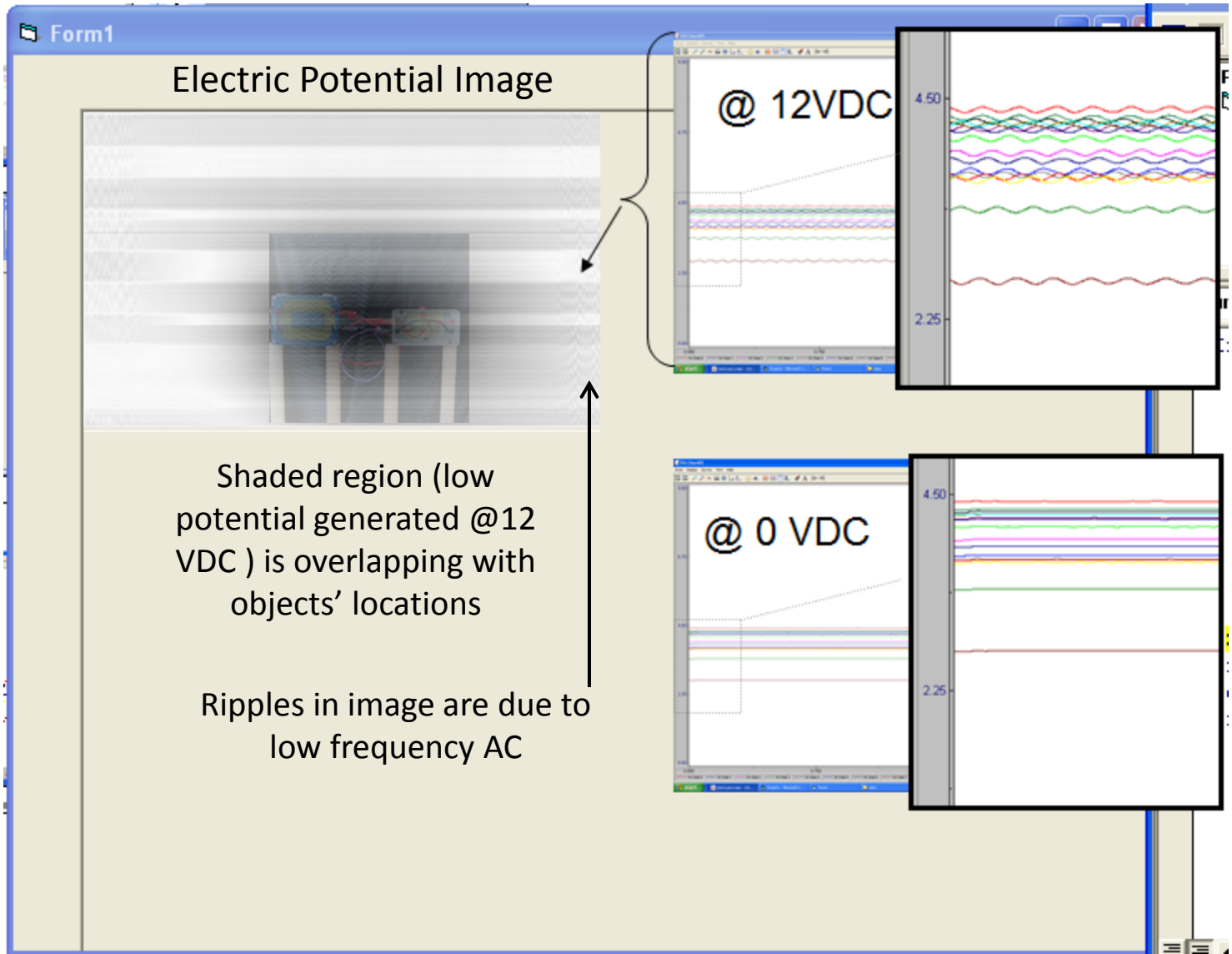
HV source on left side; RC circuit on right side (front surfaces 4” from e-Sensors) @ 12 VDC



e-Sensor Linear Array Scan - Electrical Potential Image of Hidden Active Circuit

~ 26 Hz AC waveforms observed

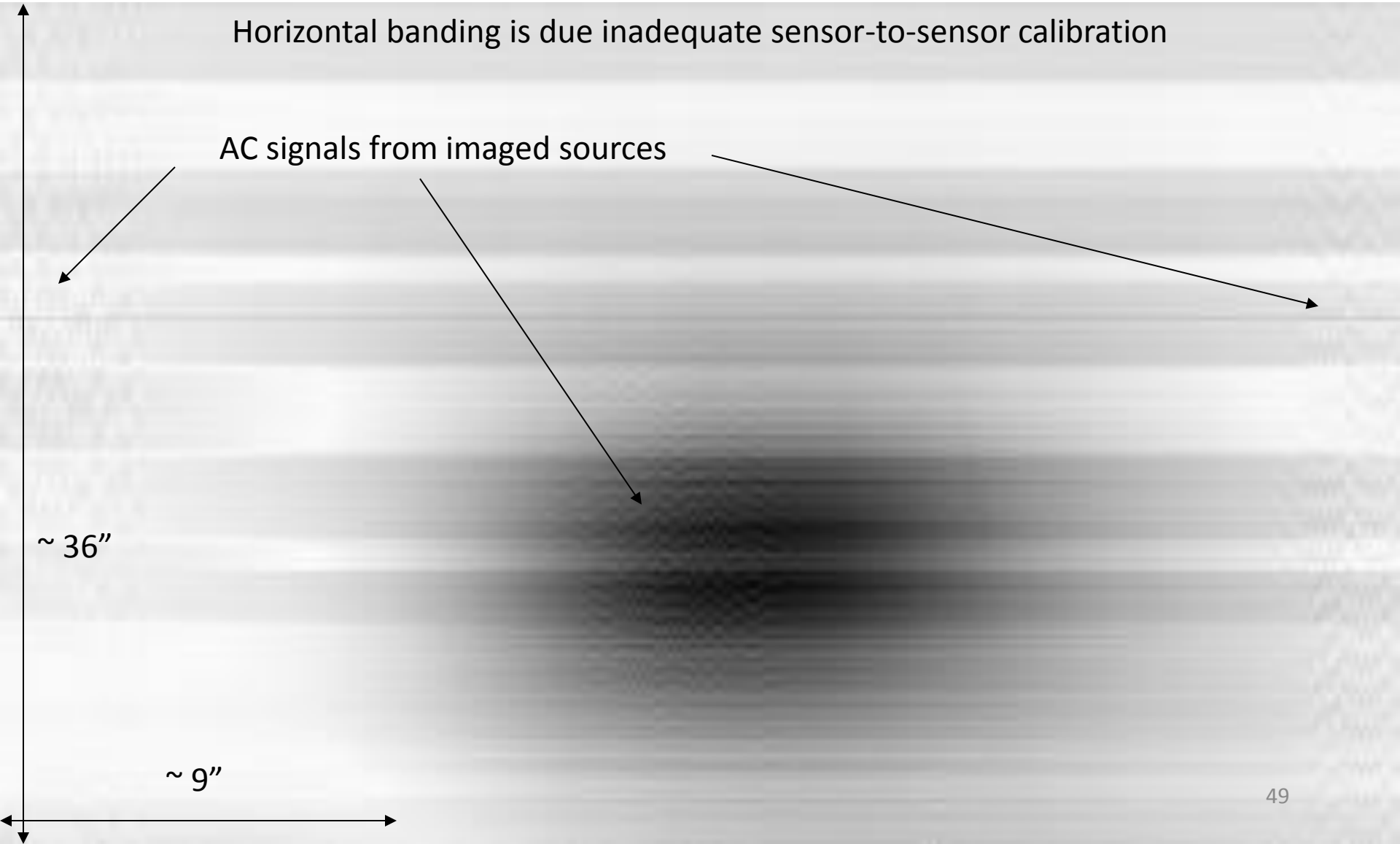
HV source on left side; RC circuit on right side (front surfaces 4” from e-Sensors) @ 12 VDC



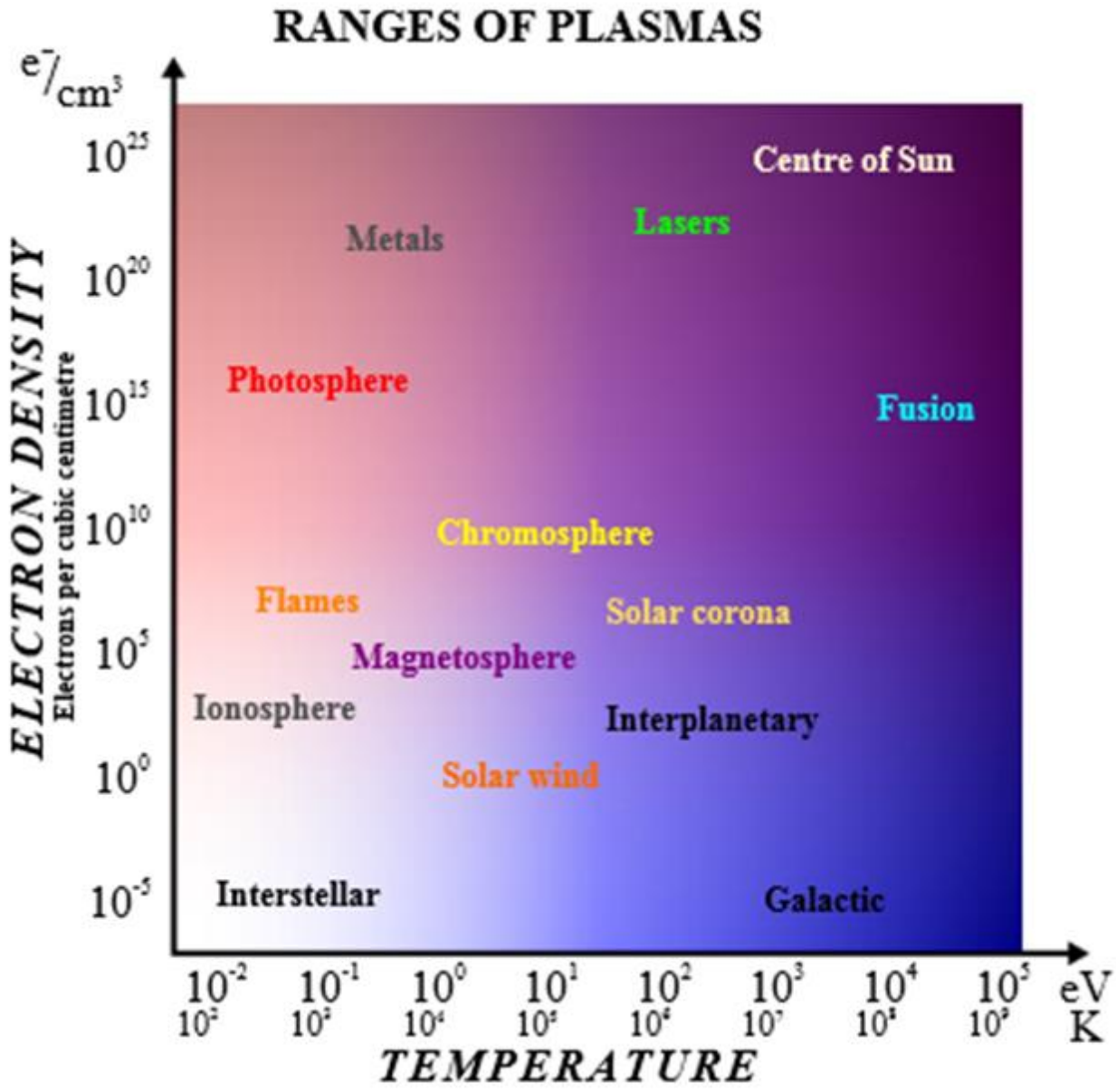
e-Sensor Linear Array Scan - Electrical Potential Image

~ 26 Hz AC waveforms observed

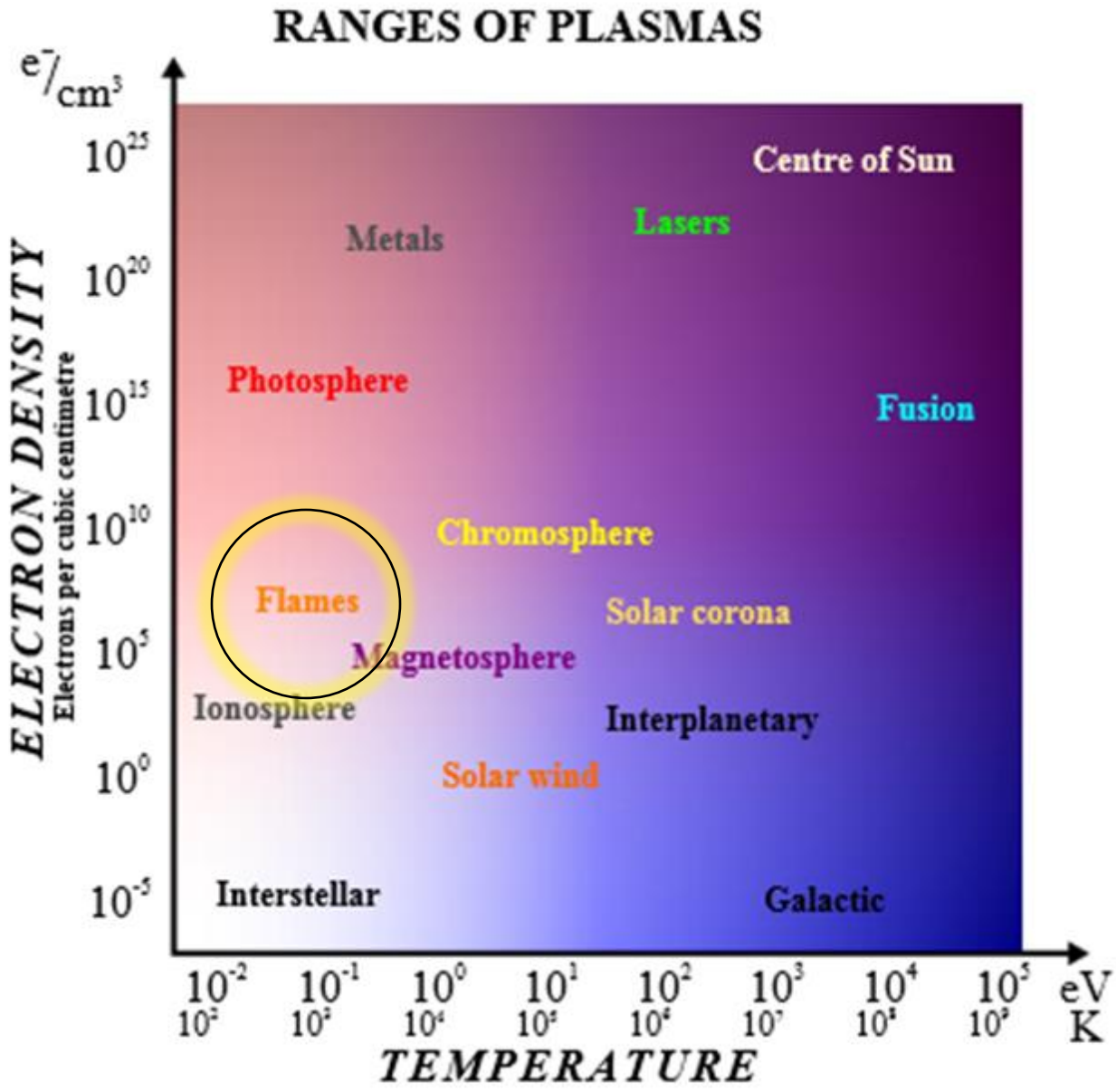
HV source on left side; RC circuit on right side (front surfaces 4” from e-Sensors) @ 12 VDC



Electric Field Imaging of Plasmas



By Jafet.vixle at English Wikipedia - Transferred from en.wikipedia to Commons., Public Domain, https://commons.wikimedia.org/w/index.php?curid=4581325



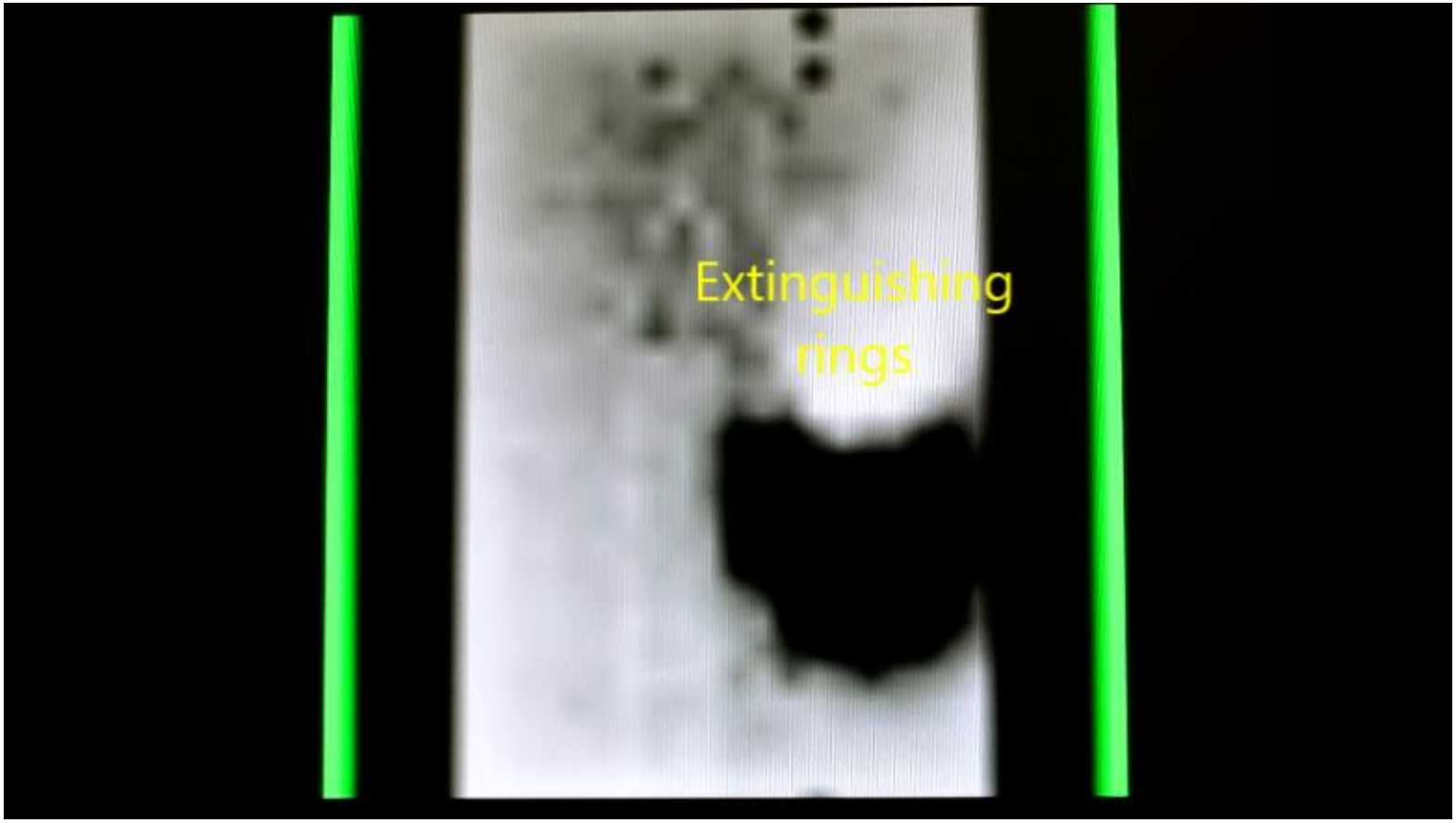
By Jafet.vixle at English Wikipedia - Transferred from en.wikipedia to Commons., Public Domain, https://commons.wikimedia.org/w/index.php?curid=4581325

Electric Potential Image

2D Electric Field Imaging of Combustion Electric Starting Lighter

August 15, 2016

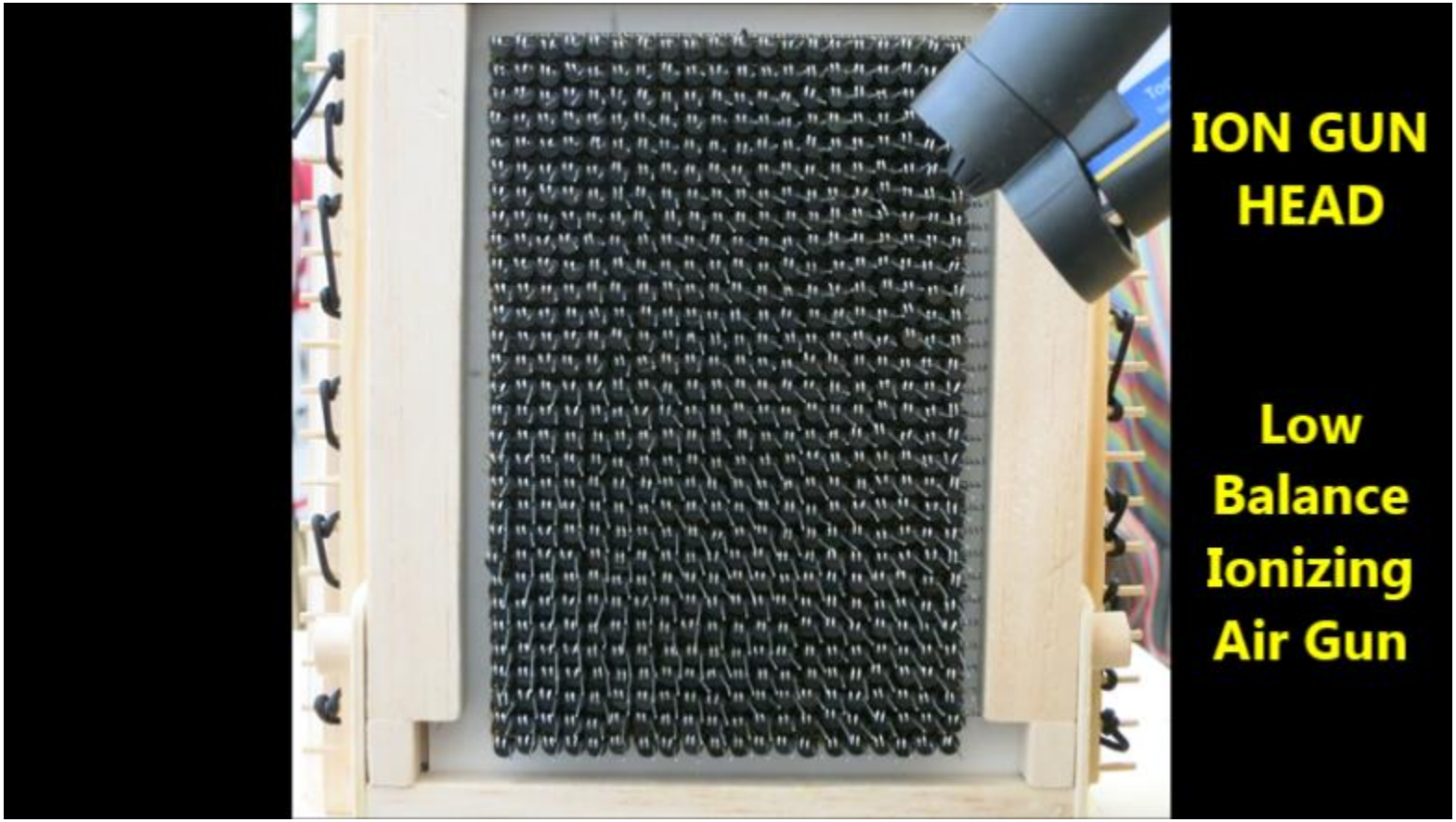
Electric Potential Image of Ignited Lighter



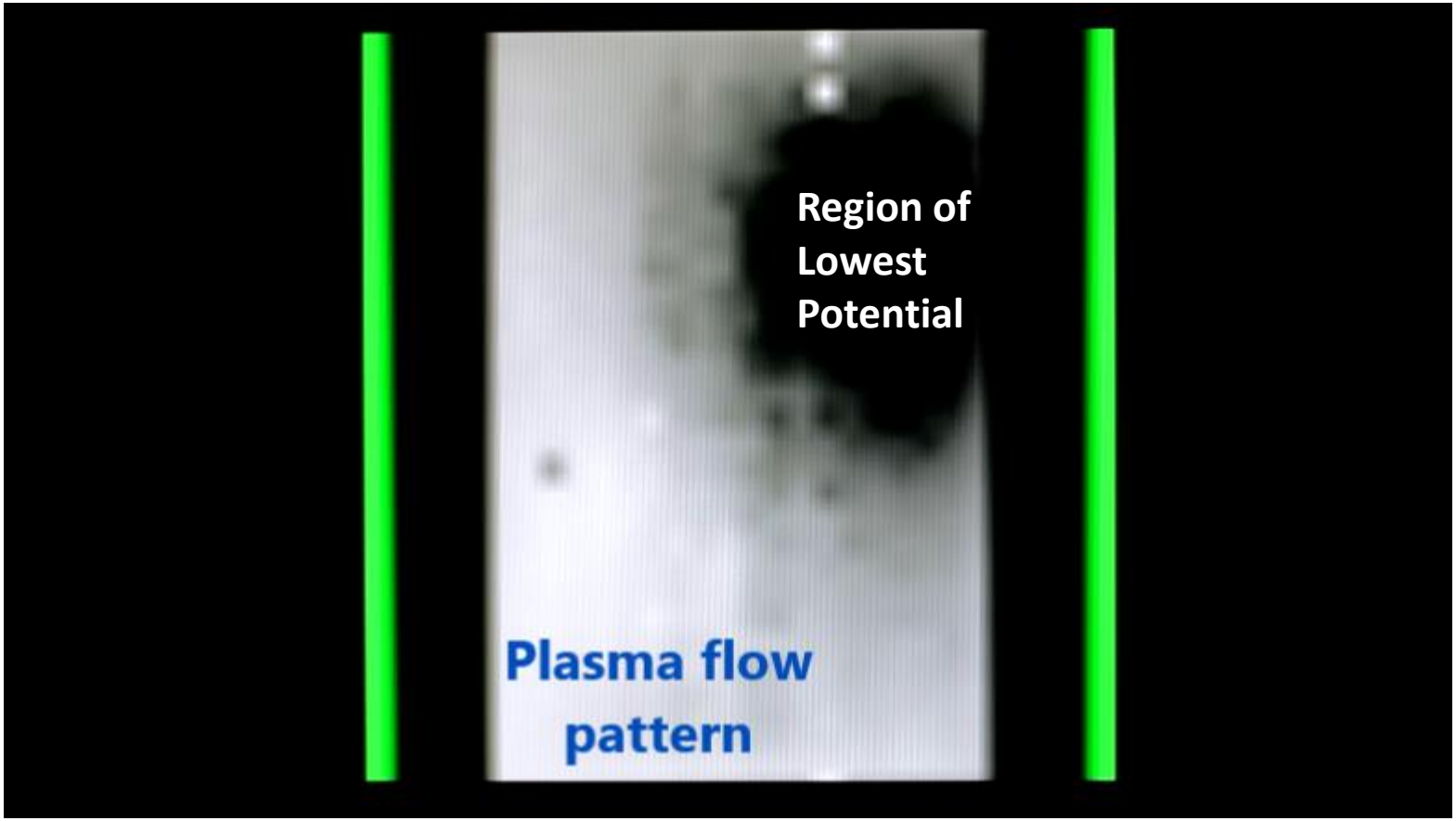
Electric Field Imaging (EFI) of Ion Gun Plasma

August 16, 2016

2D e-Sensor Array & Ion Gun



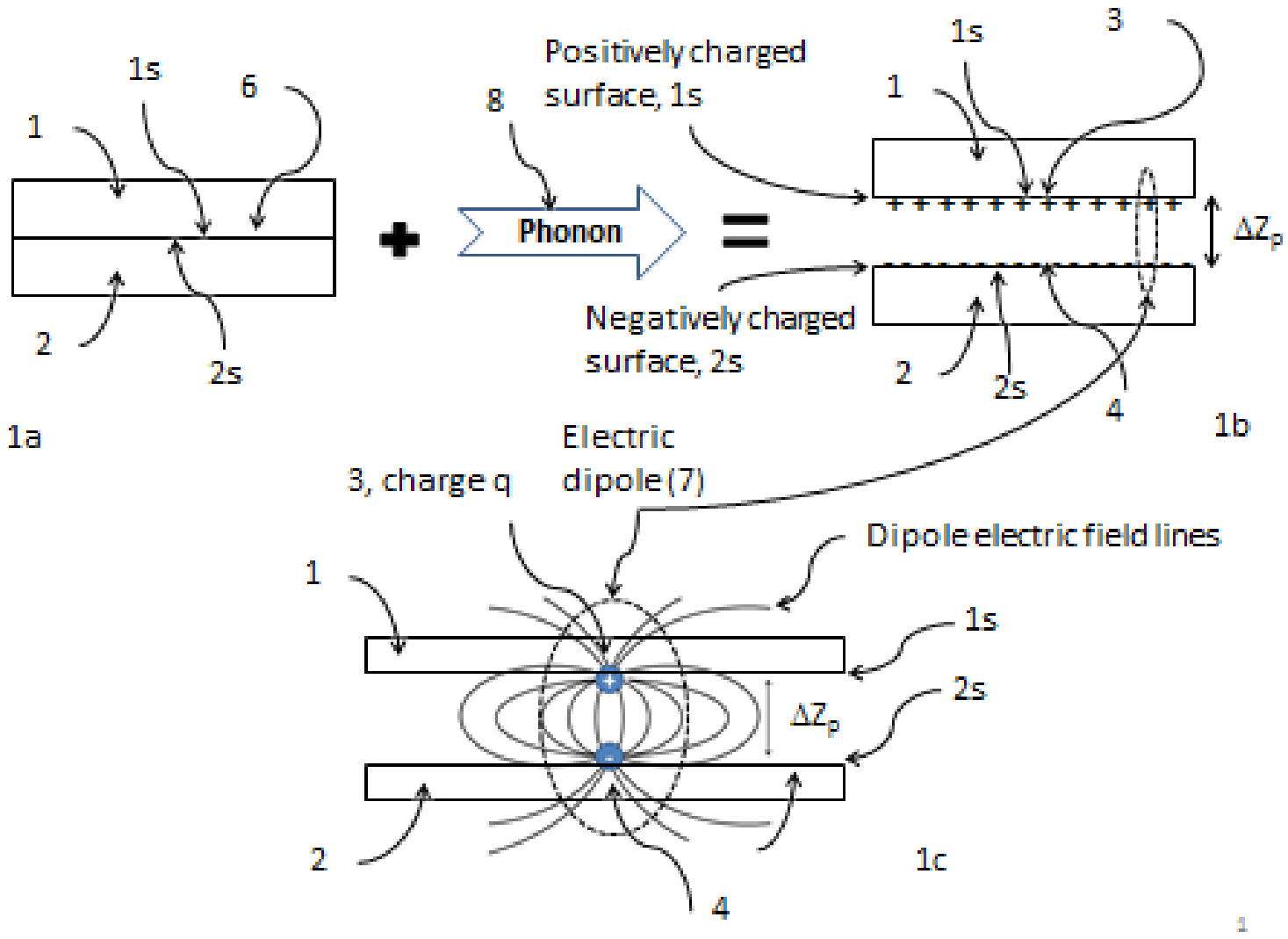
Electric Potential Image of Operating Ion Gun

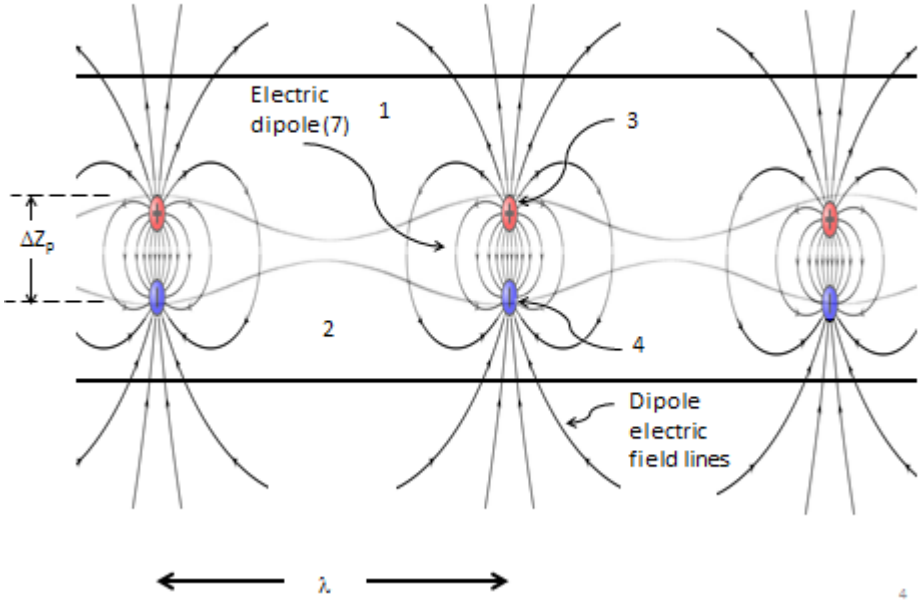


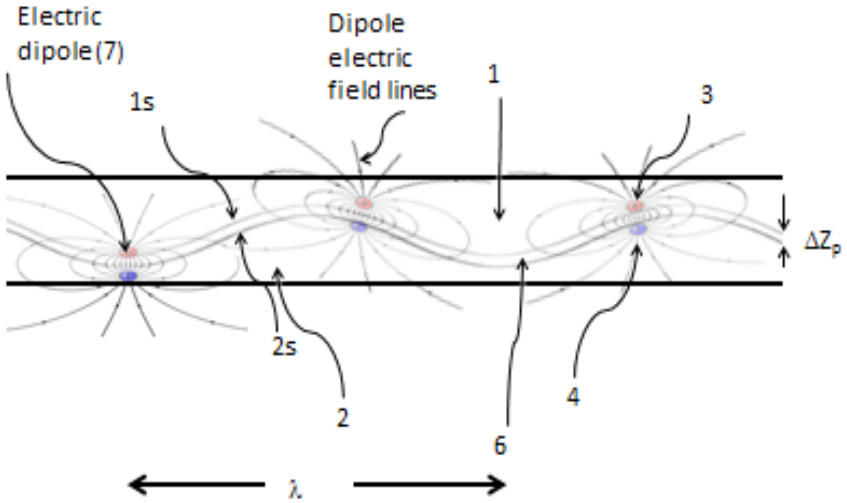
Phonon-Electric Field Imaging (EFI)

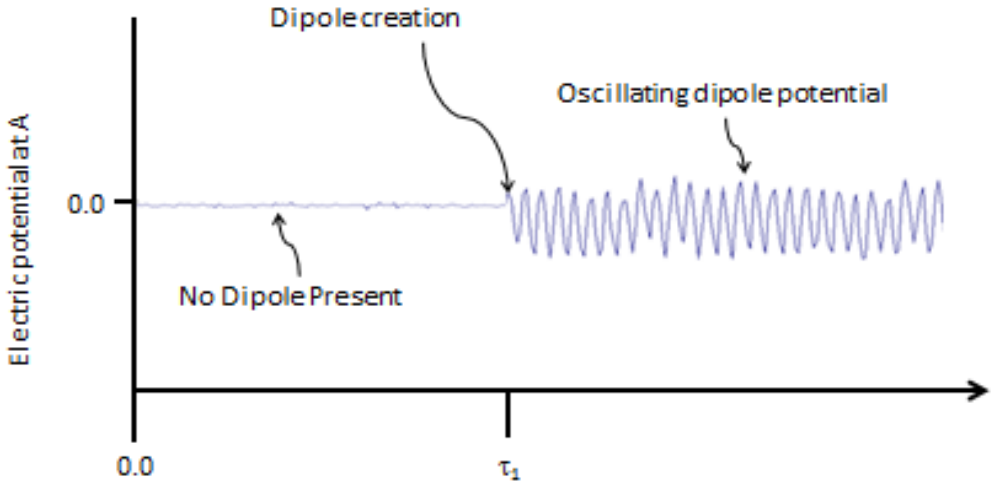
Real-time 2D EFI Array System

Phonon Assisted Dipole Creation




Electric
dipole(7)
1
3
2
4
ΔZ_p
Dipole
electric
field lines
λ


Electric
dipole(7)
1s
Dipole
electric
field lines
1
3
ΔZ_p
2s
2
6
4
λ


Dipole creation
Oscillating dipole potential
Electric potential at A
0.0
No Dipole Present
0.0
τ_1
Time, τ

Optical Image of Object

Electrical potential of phonon generated dipoles

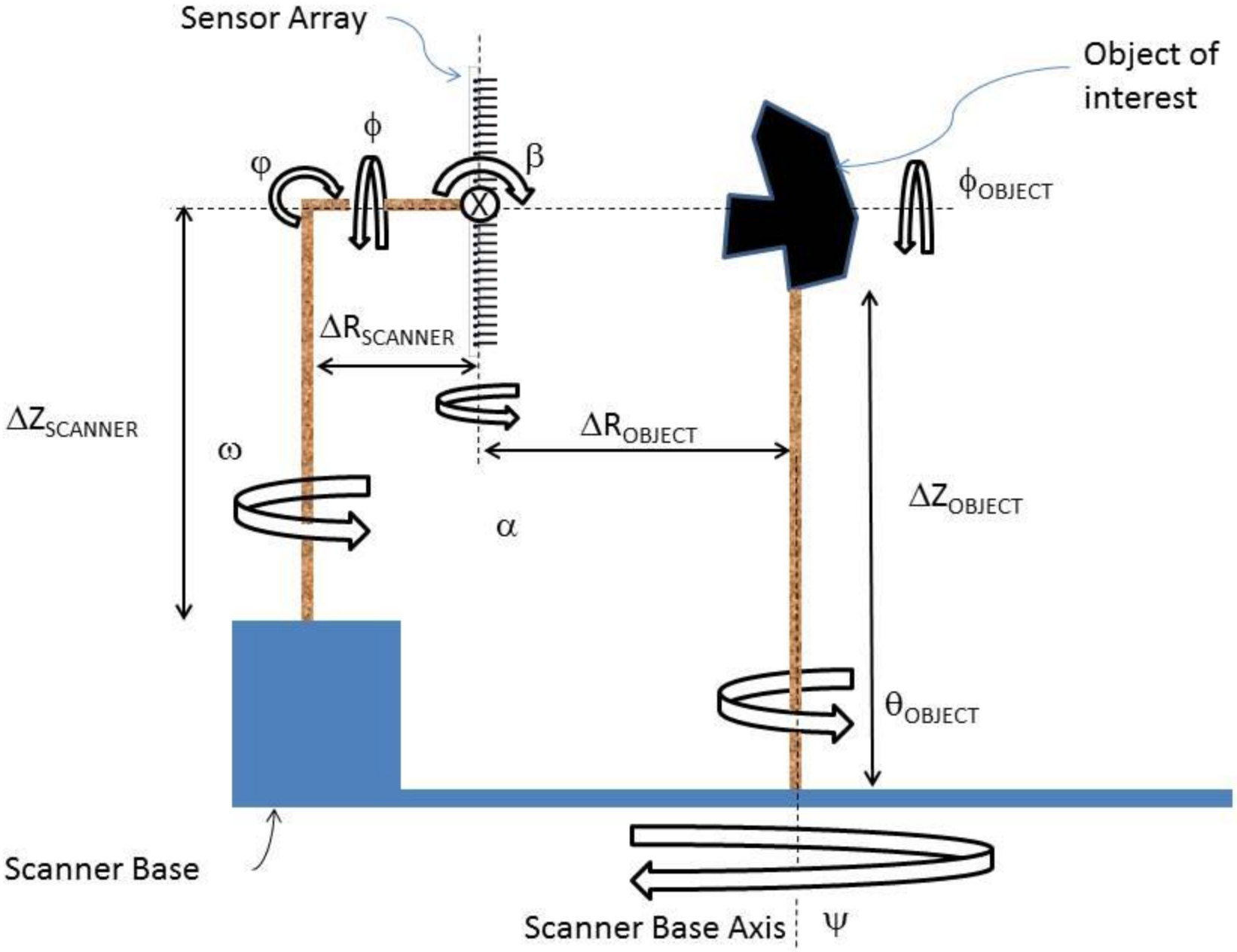
Linear grey scale
$\Delta V = 0.2$ Volts

3D Electric Field Imaging (EFI)

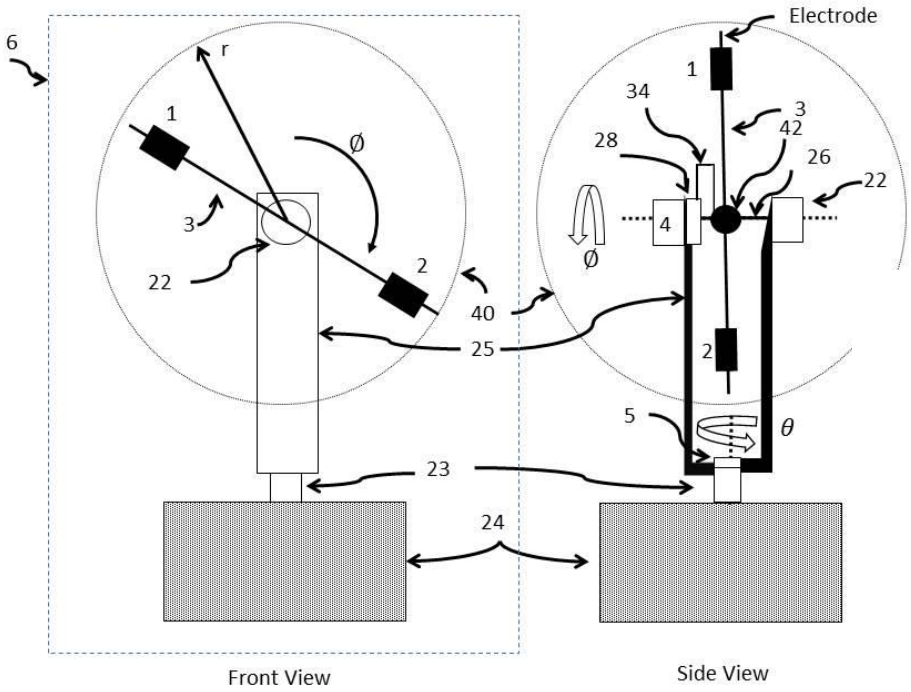
&

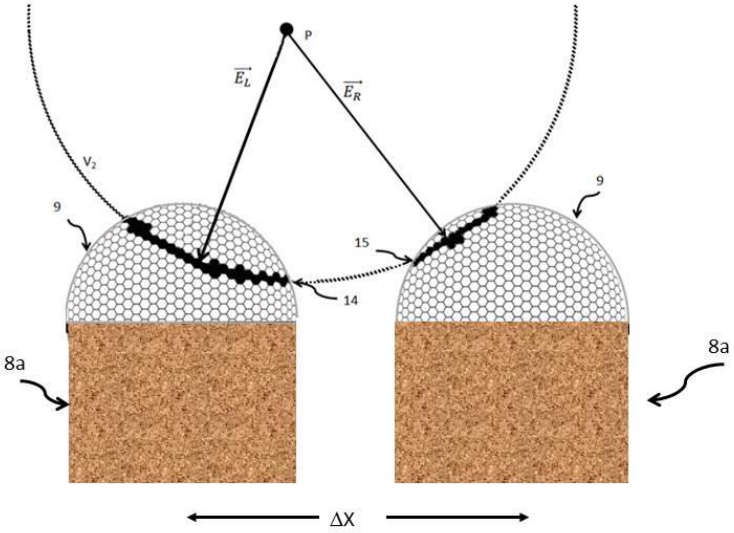
Electric Field Imaging Eye

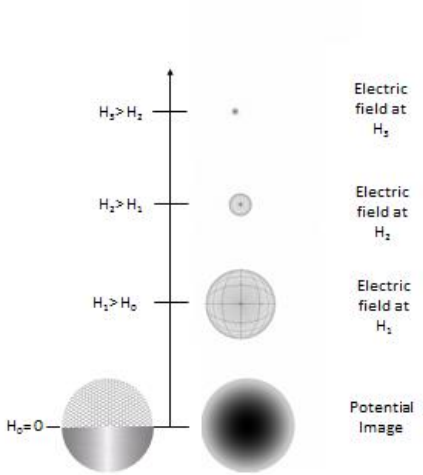
Example configuration for 3D Electric Field Imaging



Electric Field Imaging Eye







Anticipated Benefits

- **NASA Programs and Commercial space industry**
  - Electrostatic discharge (ESD) mitigation and control requirements
  - Damaged materials characterization requirements
  - Component operations and integrity
  - Remote active circuit characterization.
  - Tether and insulation quality control
  - Lightening Prediction
  - Vehicle and component charging requirements
  - Design and construction of unique electronic sensors
  - Systems and human health monitoring in space
  - Astronaut EVA safety
- **The Nation**
  - Intrusion detection
  - US perimeter security
  - Transportation security- personnel and baggage inspection
  - Personnel identification and access
  - Electronic signature requirements
  - National power grid integrity
  - Crime scene forensics
  - Molecular memory
  - Medical – non-contact EKG and EMG (electromyography)

Q & A

Patent Activities

- **Electric Field Imaging (2016) US 9279719 B2**
- **Quasi-Static Electric Field Generator (2016) US20160049885A1**
- **Ephemeral Electric Potential and Electric Field Sensor (2015) US20150137825**
- **Solid State Ephemeral Electric Potential and Electric Field Sensor**, Serial Number: 15/177,798 (2016)
- **Dynamic Multidimensional Electric Potential and Electric Field Quantitative Measurement System and Method** , US Serial Number: 62/357,407 (2016)
- **Solid State Ephemeral Electric Potential and Electric Field Sensor**, US Serial Number: 15/177798 (2016)
- **Dynamic Multidimensional Electric Potential and Electric Field Quantitative Measurement System and Method**, US Serial Number: 62/357,407 (2016)
- LAR-19005-1 **Electric Field Imaging Eye,** Provisional Patent Application (2017)
- LAR-19007-1 **Method for Phonon Assisted Creation and Annihilation of Subsurface Electric Dipoles**, Provisional Patent Application (2017)

For EFI technology listing and licensing opportunities:

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https://technology.nasa.gov/patent/LAR-TOPS-116

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