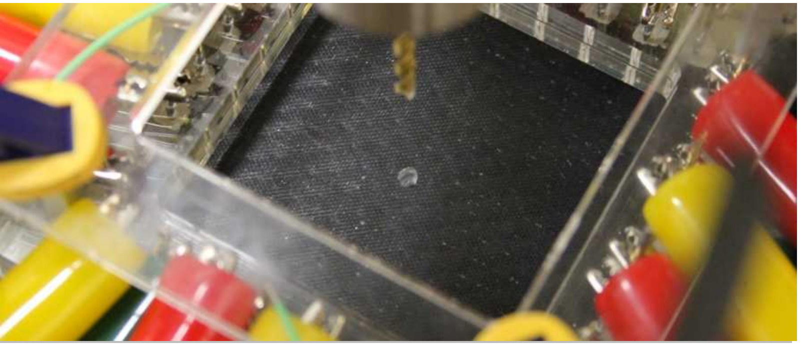
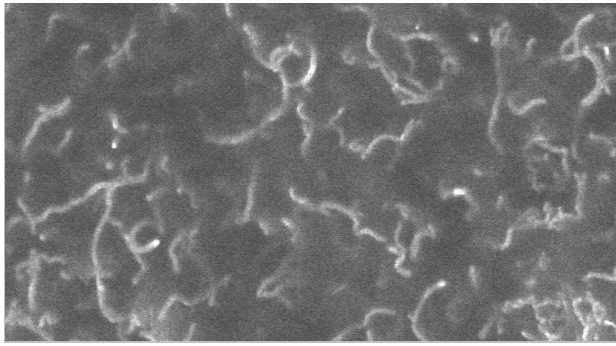
SAND2016-5611PE

Exceptional service in the national interest

Sandia National Laboratories





Spatially Distributed Structural Health Monitoring using Electrical Impedance Tomography

Bryan R. Loyola[1]

[1]Sandia National Laboratories, Livermore, CA, USA

U.S. DEPARTMENT OF ENERGY

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

NNSA National Nuclear Security Administration

Usage of Fiber-Reinforced Composites

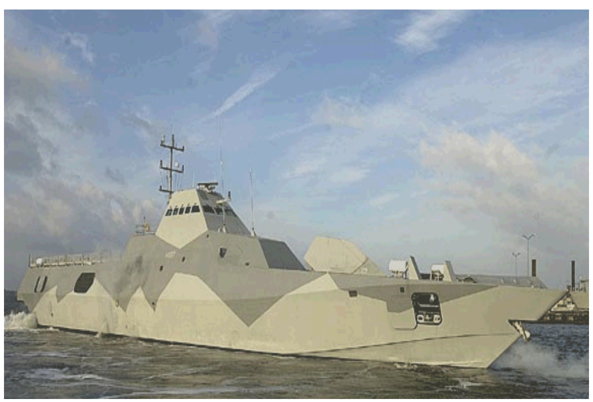
Sandia National Laboratories

- Over the past 50 years, increased usage of composite materials

Commercial aircraft systems

Future and legacy spacecraft

Military aircraft



Naval structures

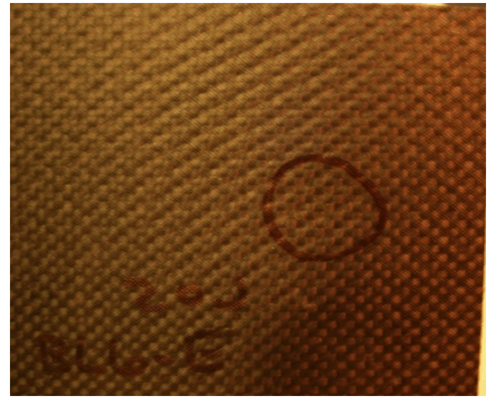
Wind turbine blades

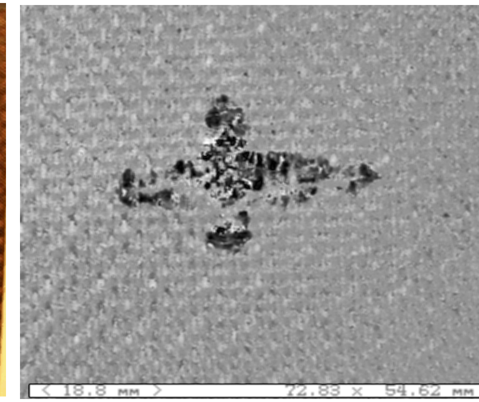
CFRP cable stay bridge

Composite Damage Modes

Sandia National Laboratories

- Susceptible to damage due to:
  - Strain, impact, chemical penetrants, multi-axial fatigue
- Damage modes:
  - Matrix cracking
  - Fiber-breakage
  - Delamination
  - Transverse cracking
  - Fiber-matrix debonding
  - Matrix degradation
  - Blistering
- Difficult to detect
  - Internal to laminate structure
  - Nearly invisible to naked eye
  - Current methods are laborious





Visual inspection **C-SCAN ultrasound image**

CFRP panel after 20 Joule impact

Aircraft ultrasonic inspection (Composites World)

Catastrophic Failure

- Occurred in 2002 – one of the worst fire seasons in previous 50 yrs.
- Event caused grounding of fleet (33 aircraft) severely reducing resources
- Wikipedia

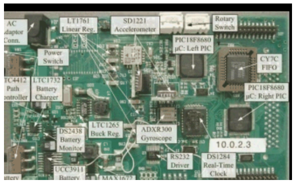
- Reliability Engineering
  - Replacement based on predetermined max lifetime/lifecycles
  - High cost
    - F-35 maintenance will cost est. $1.1T during lifetime

F-35A Lightning II (Lockheed Martin)

- Reliability paradigm shift
  - Event driven replacement
  - Lower cost
  - Save lives

Emerging Sensing Technologies

Wireless Sensors and Sensor Networks



WiMMS UCI DuraNode

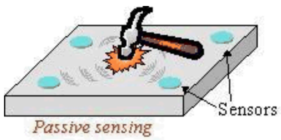
Wang, *et a*

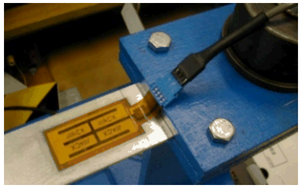
- **Adva**
  -
  -
  -
- **Disad**
  -
  -
  -

FIX

Strain gages, DIC, fiber optics, embedded piezos

Ultrasonics and Guided-Waves

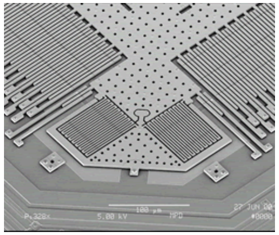


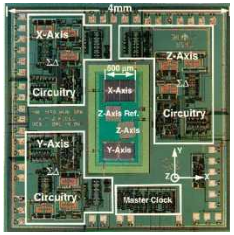


Array of piezoelectric ceramic sensors and actuators

- **dvantages:**
  - Sensors and actuators
  - Spatial damage detection
- **isadvantages:**
  - Indirect damage detection
  - Wave propagation models or pattern recognition
  - Thin structures
  - Expensive data acquisition

Micro-electromechanical Systems (MEMS)





AD *i*MEMS Weinberg (1999)

3-axis accelerometer Lemkin (1997)

- **Advantages:**
  - Miniaturized sensor designs
  - Complex sensors/actuators
- **Disadvantages:**
  - “Top-down” design
  - Expensive fabrication equipment
  - High costs
  - Sensor sensitivity on par with macro-scale counterpart

SHM Design Considerations

Current SHM limitations:

- Indirect sensing approaches
- Point-based sensing
- Tethered sensors
- Lack of system scalability

Boeing 787 (Boeing)

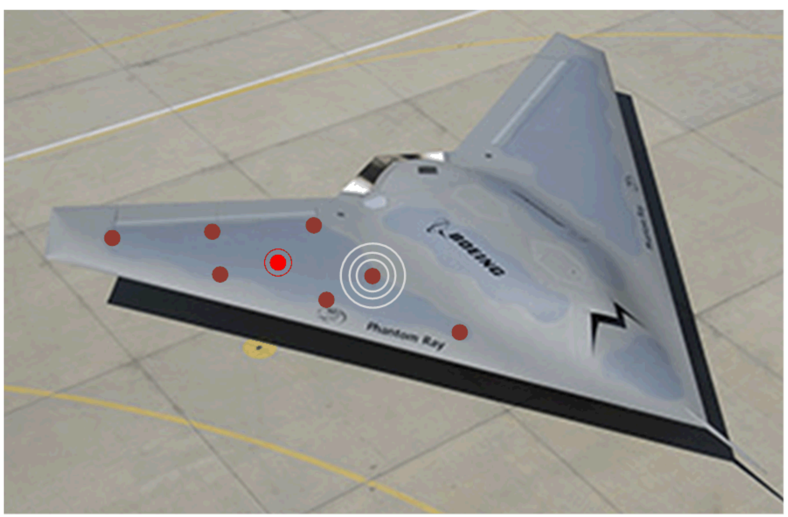
Successful SHM systems:

1. Directly detect and measure damage
2. Determine the damage location
3. Ascertain the size of the damage
4. Quantify the severity of the damage
5. Achieve multi-modal sensing capabilities (i.e., delamination, cracking, and chemical penetration)

Golden Gate Bridge (Wikipedia)

Spatially Distributed SHM Paradigm

- Current state-of-art in structural health monitoring:
  - Passive SHM using acoustic emissions
  - Active SHM using piezoelectric sensor/actuator pairs
- "Sensing skins" for spatial damage detection:
  - Objective is to identify the location and severity of damage
  - Monitor and detect damage over two- (or even three) dimensions
  - Direct damage detection

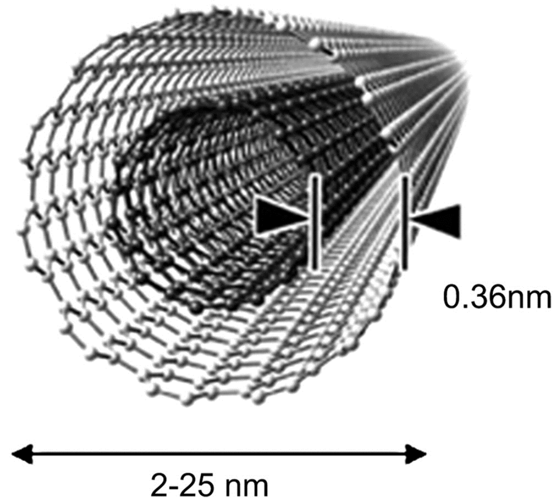


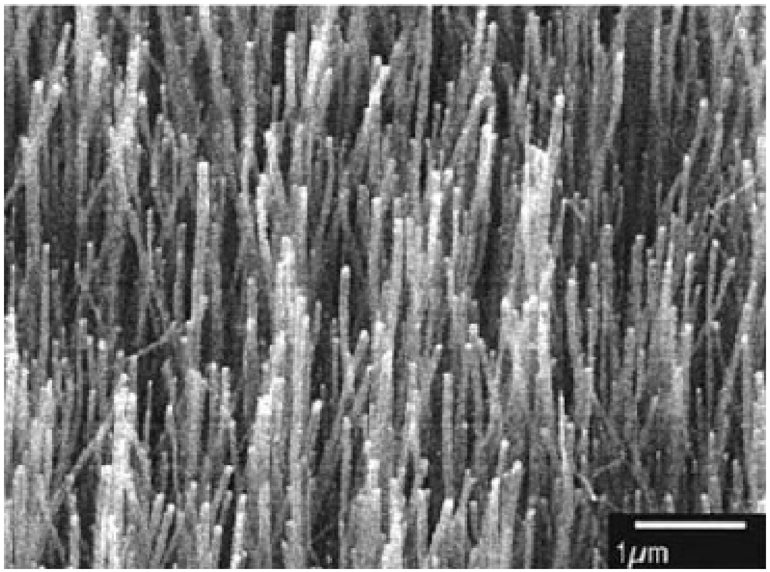
(Boeing)

(Boeing)

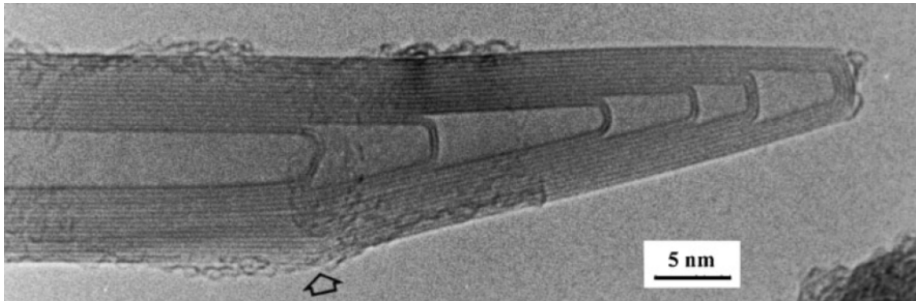
Carbon Nanotubes

- Multi-walled carbon nanotubes (MWNT):
  - Rolled concentric cylindrical structures constructed of graphene sheets
  - Diameter: 6 ~ 100 nm
  - High-aspect ratios: ~10^3 to 10^7
  - Metallic conductivity
  - Five times stiffer and ten times stronger than steel





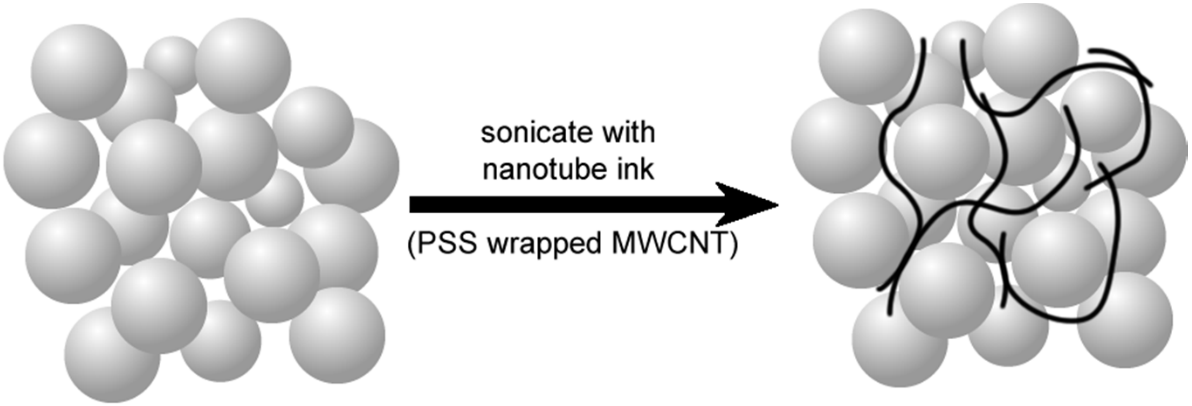
Aligned carbon nanotube forest
Thostenson, et al. (2001)



TEM imagery of an end cap of a MWNT
Harris (2004)

Sprayable MWNT-Latex Thin Film

- Rapid large-scale deposition
  - Required for mass deployment of methodology
- MWNT-PSS/Latex paint formulation
  - Collaborated to improve initial Sandia formulation
  - Sub-micron PVDF creates mold for MWNT organization
  - Off-the-shelf deposition method



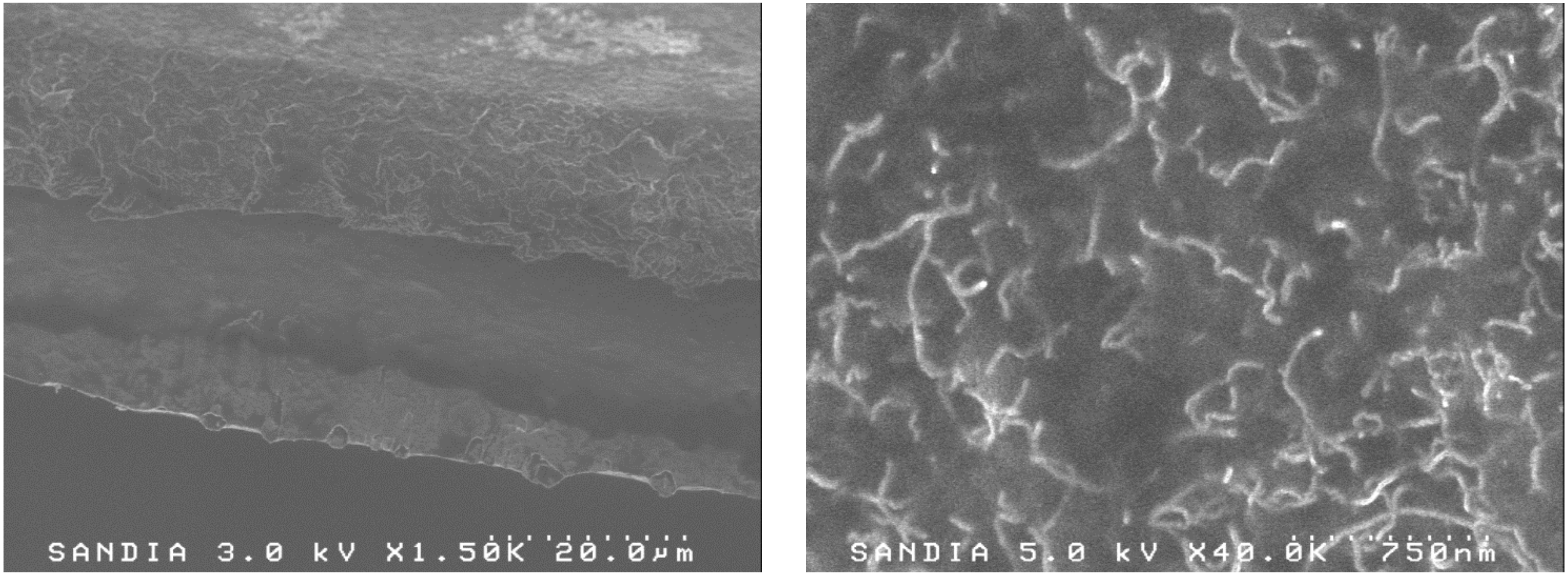
Kynar Aquatec™ latex solution (avg. particle size 150nm)

Forms segregated MWCNT network

MWNT-Latex Morphology

- Creation of MWNT networks:
  - Electrical percolation above 1 wt% MWNTs

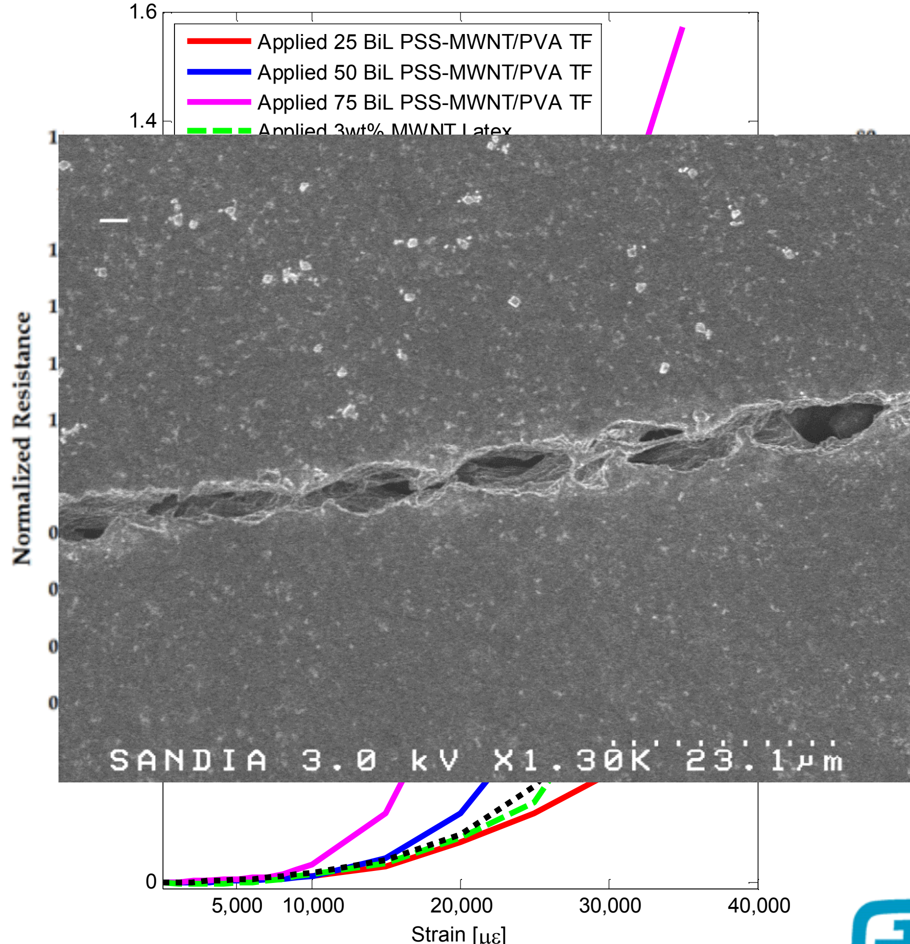
- Fiber-reinforced polymer deployment:
  - Surface applied to post-cured composites
  - Applied to fiber weaves for embedded sensing



Cross-section and MWNT network SEM images of 3wt% MWNT-Latex film

MWNT-Latex Characterization

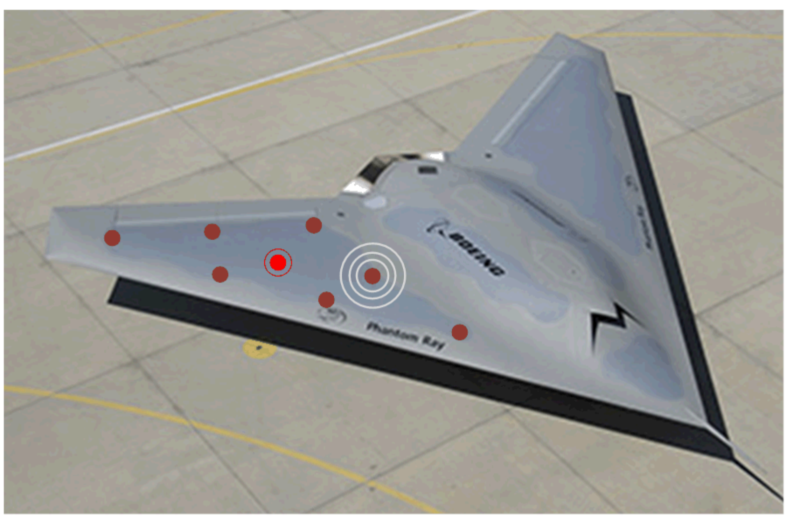
- Electromechanical characteristics:
  - Quasi-static testing
    - Nearly same sensitivity as LbL
  - Bi-functional strain response
    - Linear
    - Quadratic
      - Cracking of film
- Thermo-resistance coupling:
  - -50° C to 80° C over 2 hours
  - 2 hour holds
  - Inversely linear relationship
  - Non-linear response @ -30° C
    - ~ T_g of PVDF
    - Restructuring of MWNTs



Spatially Distributed SHM Paradigm

Sandia National Laboratories

- Current state-of-art in structural health monitoring:
  - Passive SHM using acoustic emissions
  - Active SHM using piezoelectric sensor/actuator pairs
- "Sensing skins" for spatial damage detection:
  - Objective is to identify the location and severity of damage
  - Monitor and detect damage over two- (or even three) dimensions
  - Direct damage detection

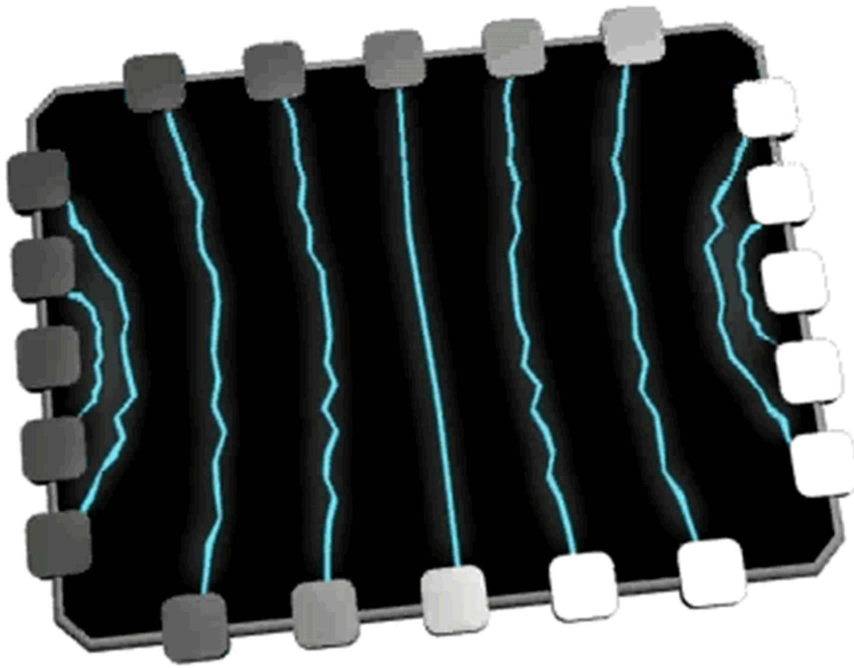


(Boeing)

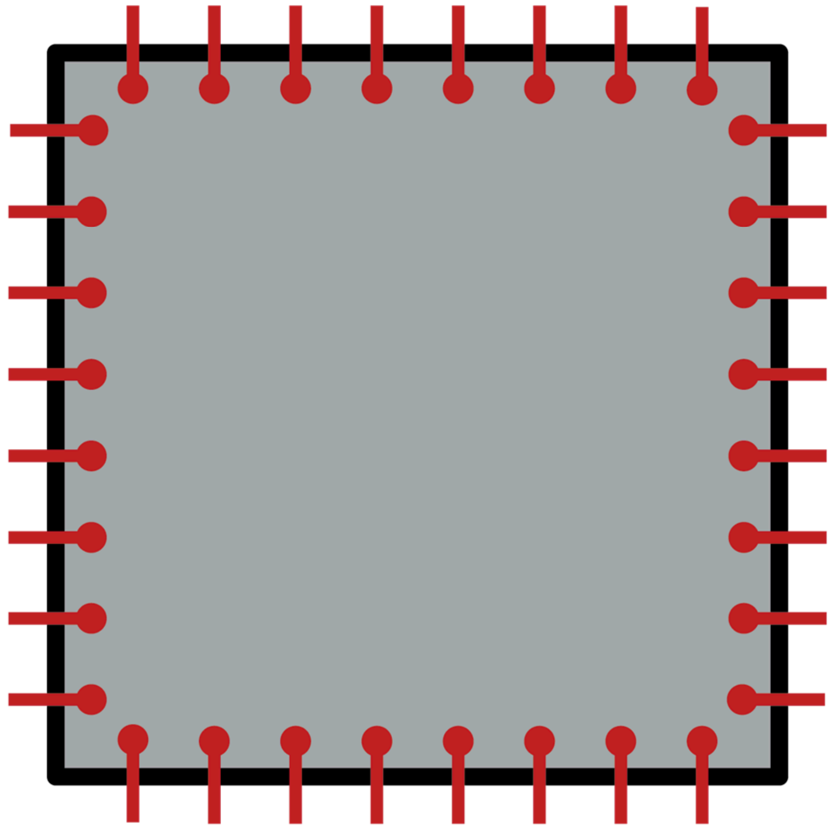
(Boeing)

Electrical Impedance Tomography

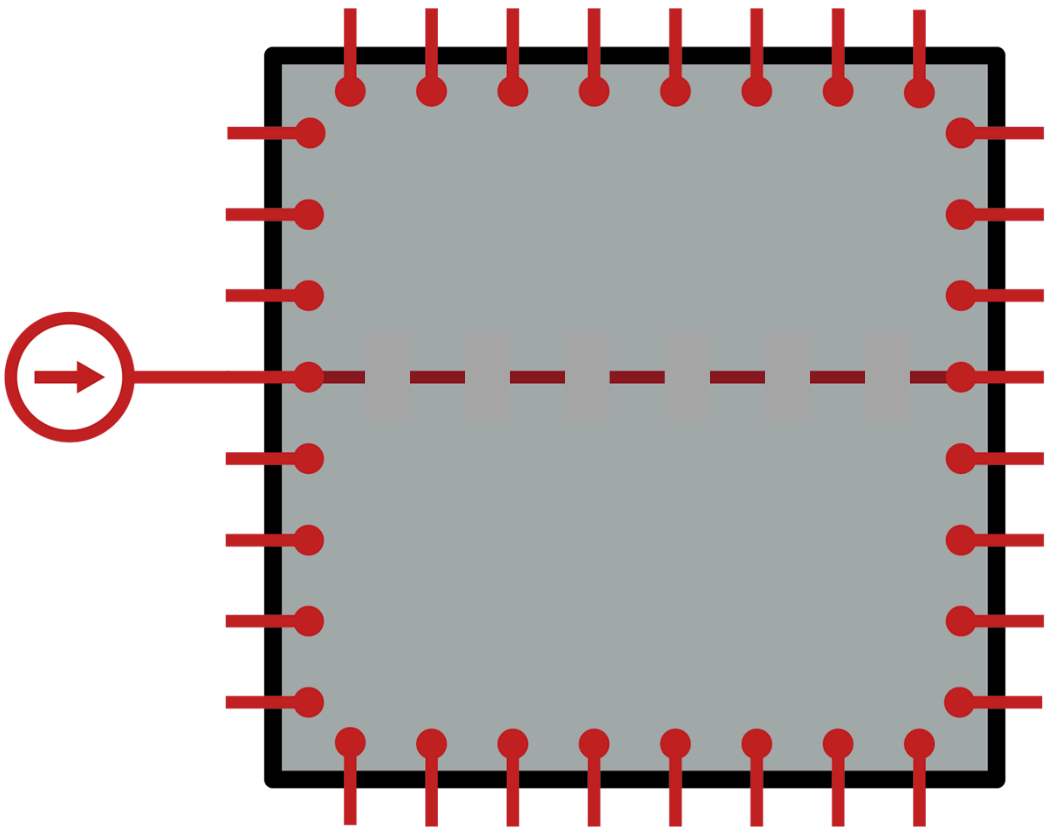
- Overview of spatial conductivity mapping
  - Since film impedance calibrated to strain, conductivity maps can correspond to 2-D strain distribution maps



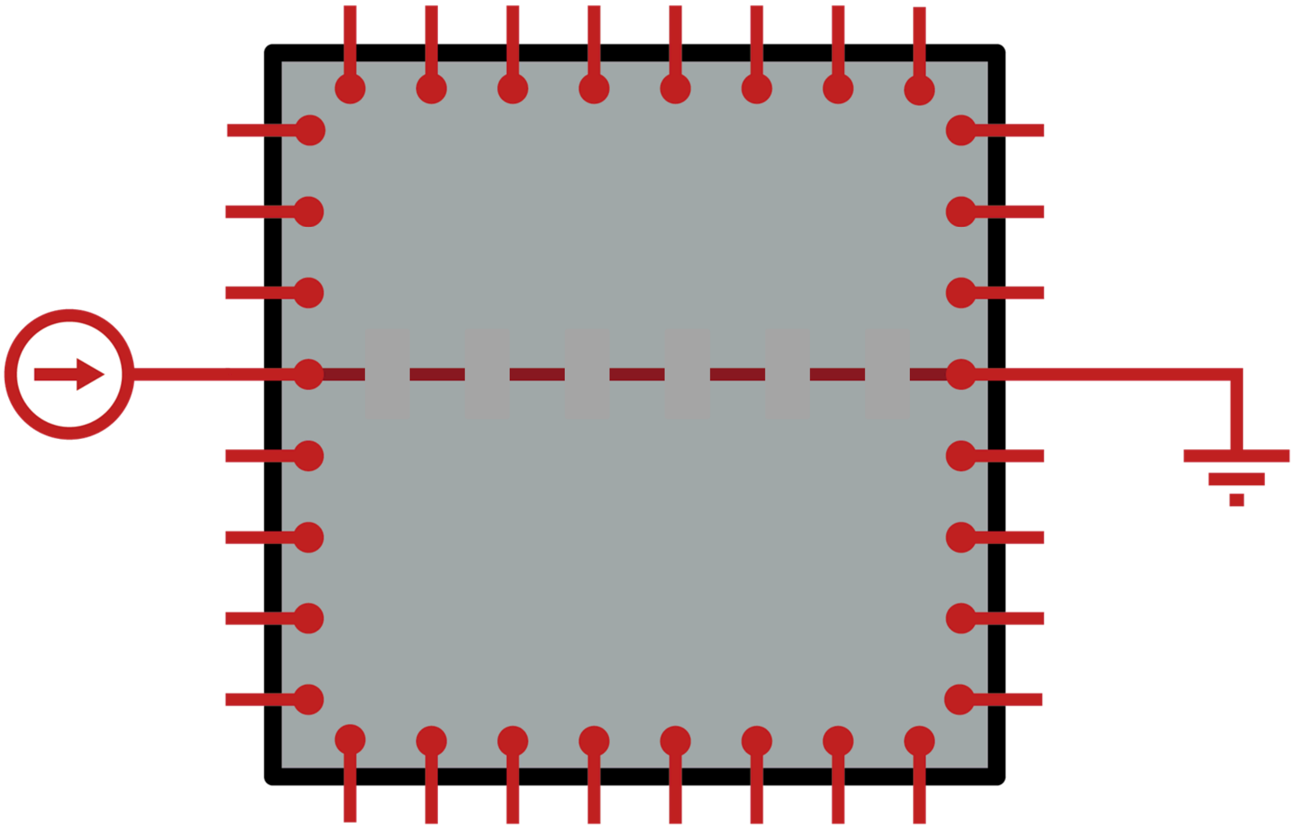
EIT Measurements



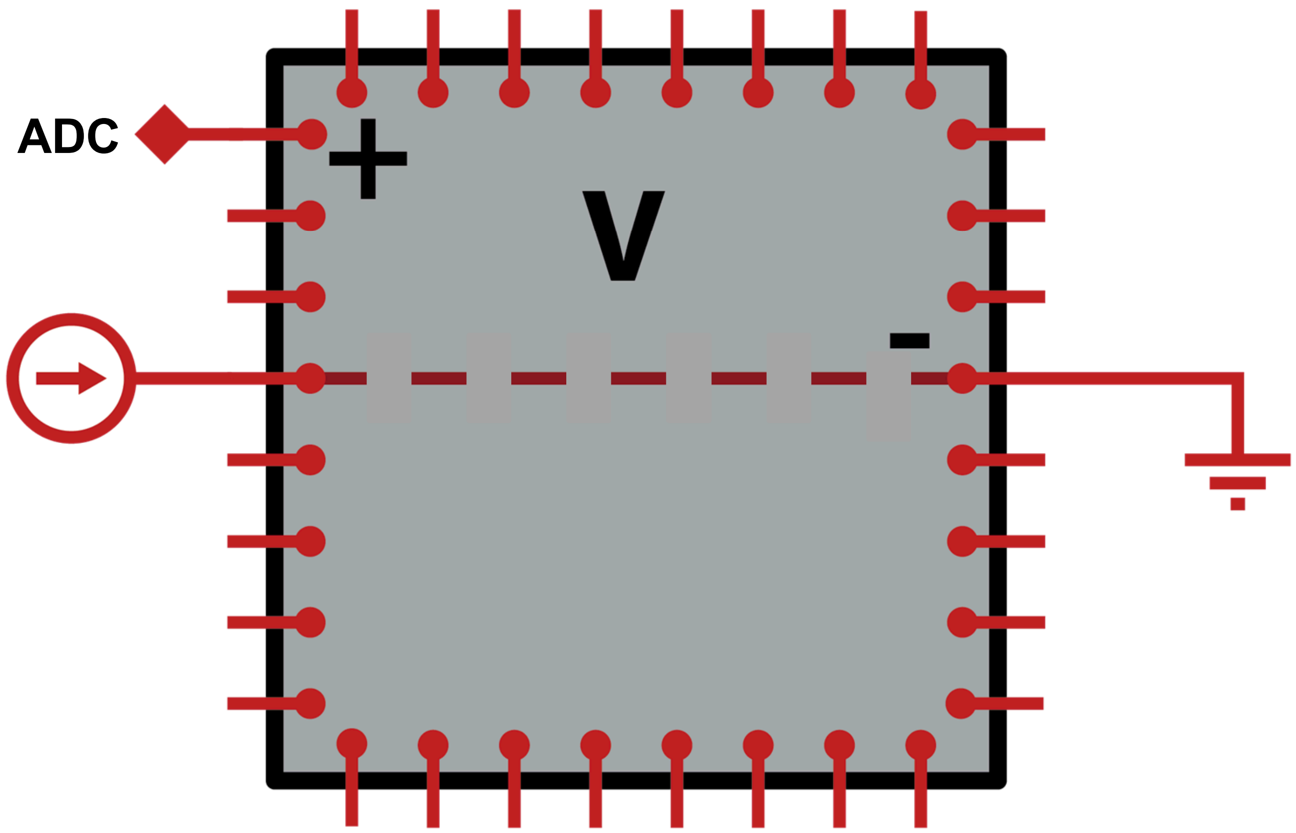
EIT Measurements



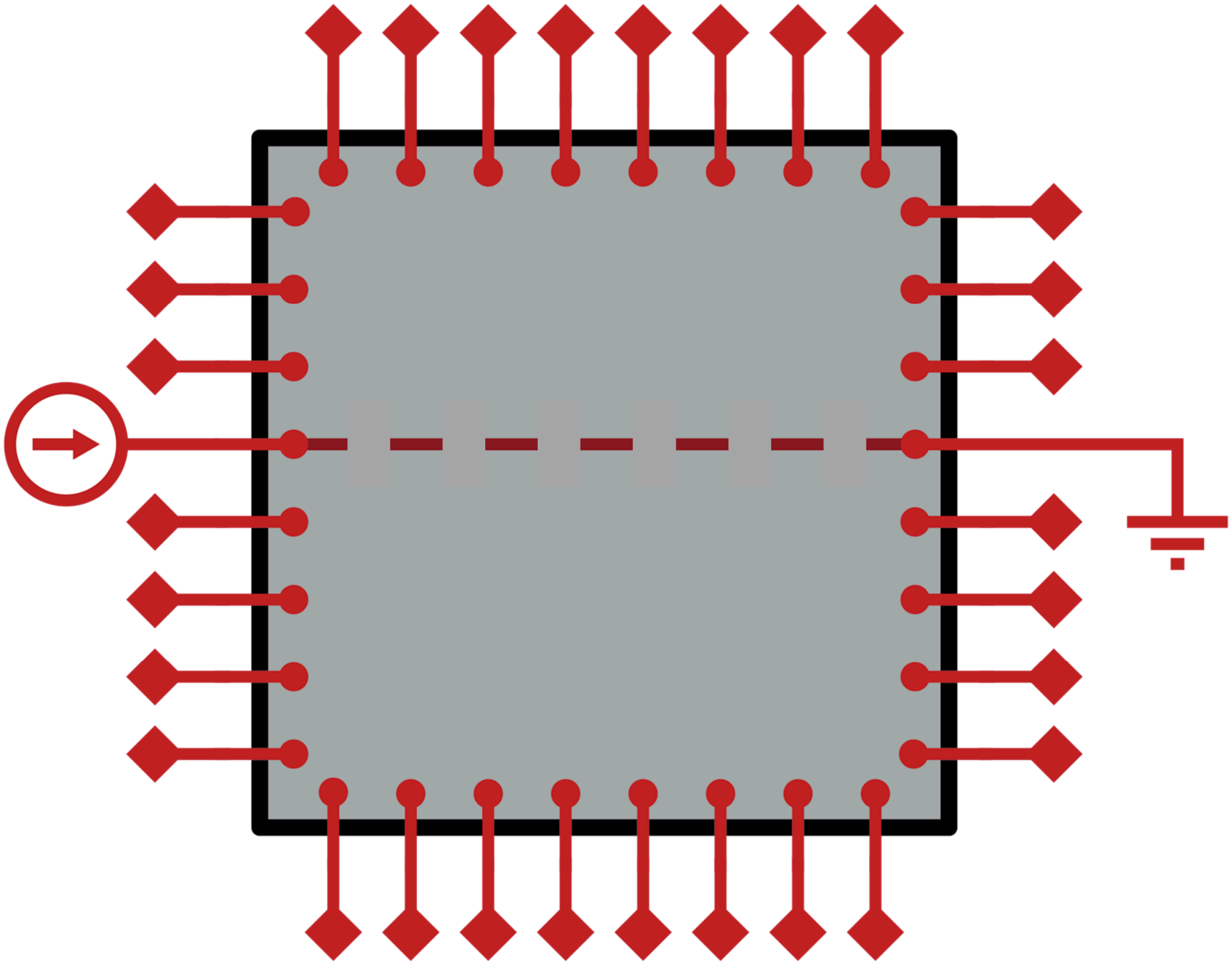
EIT Measurements



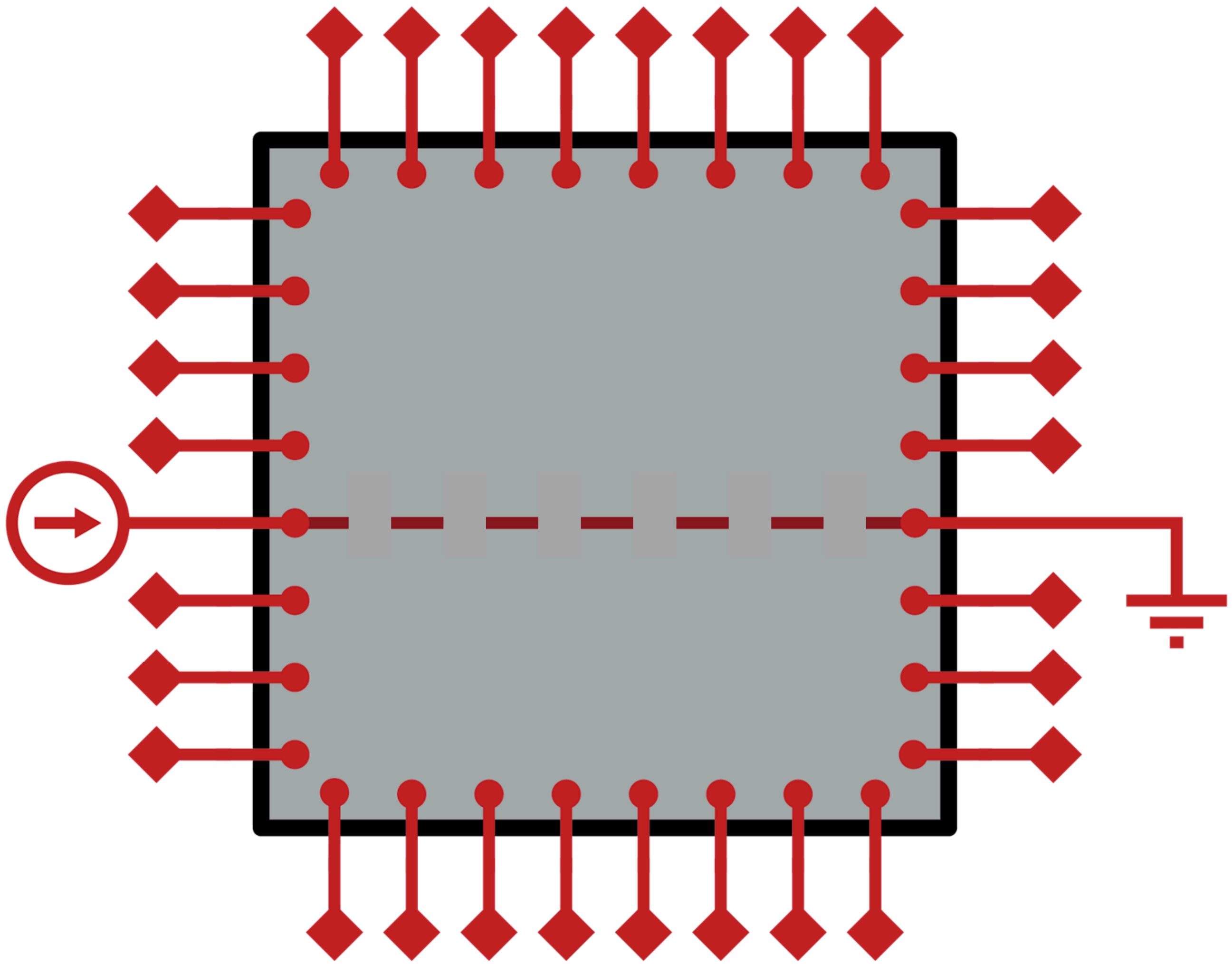
EIT Measurements



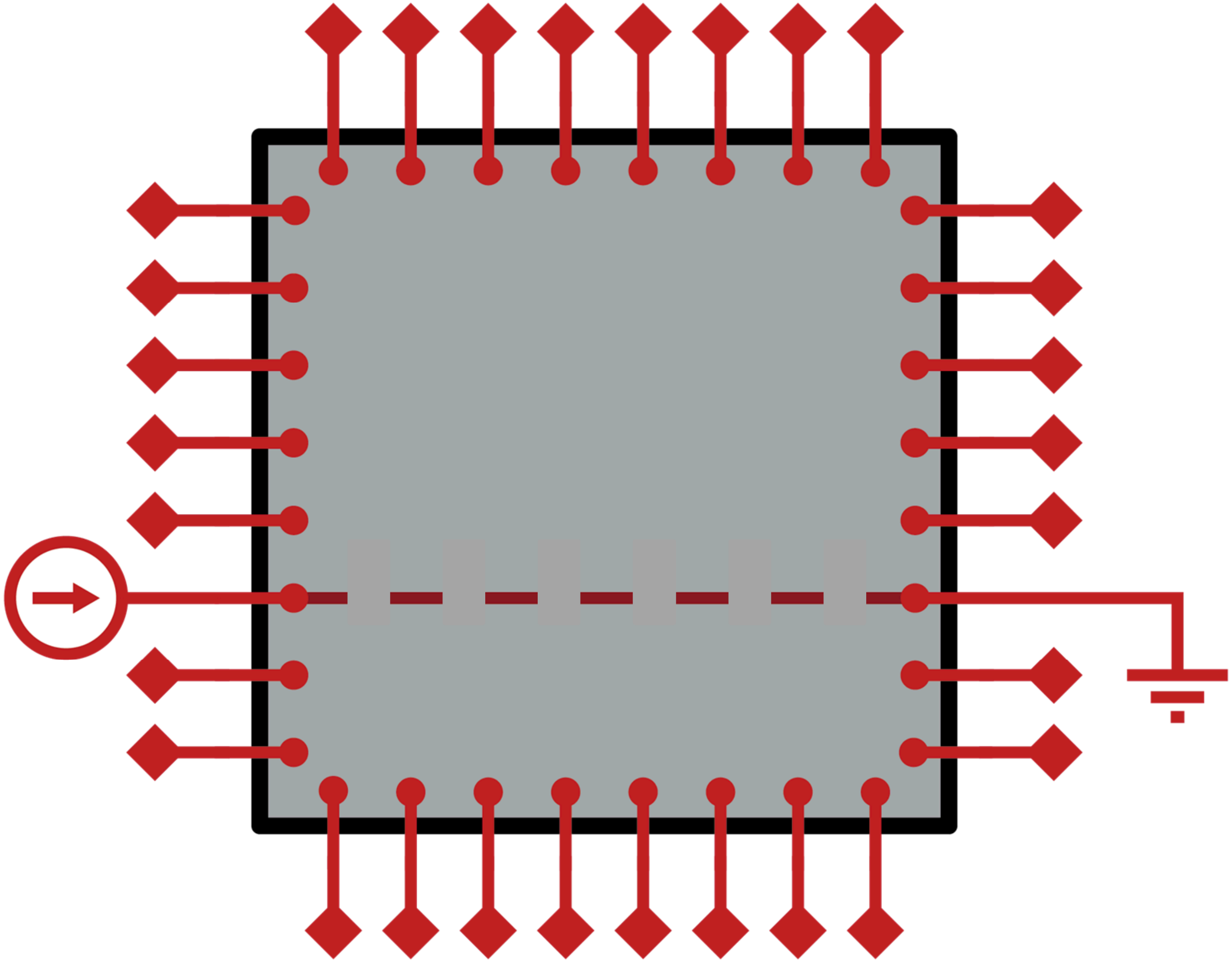
EIT Measurements



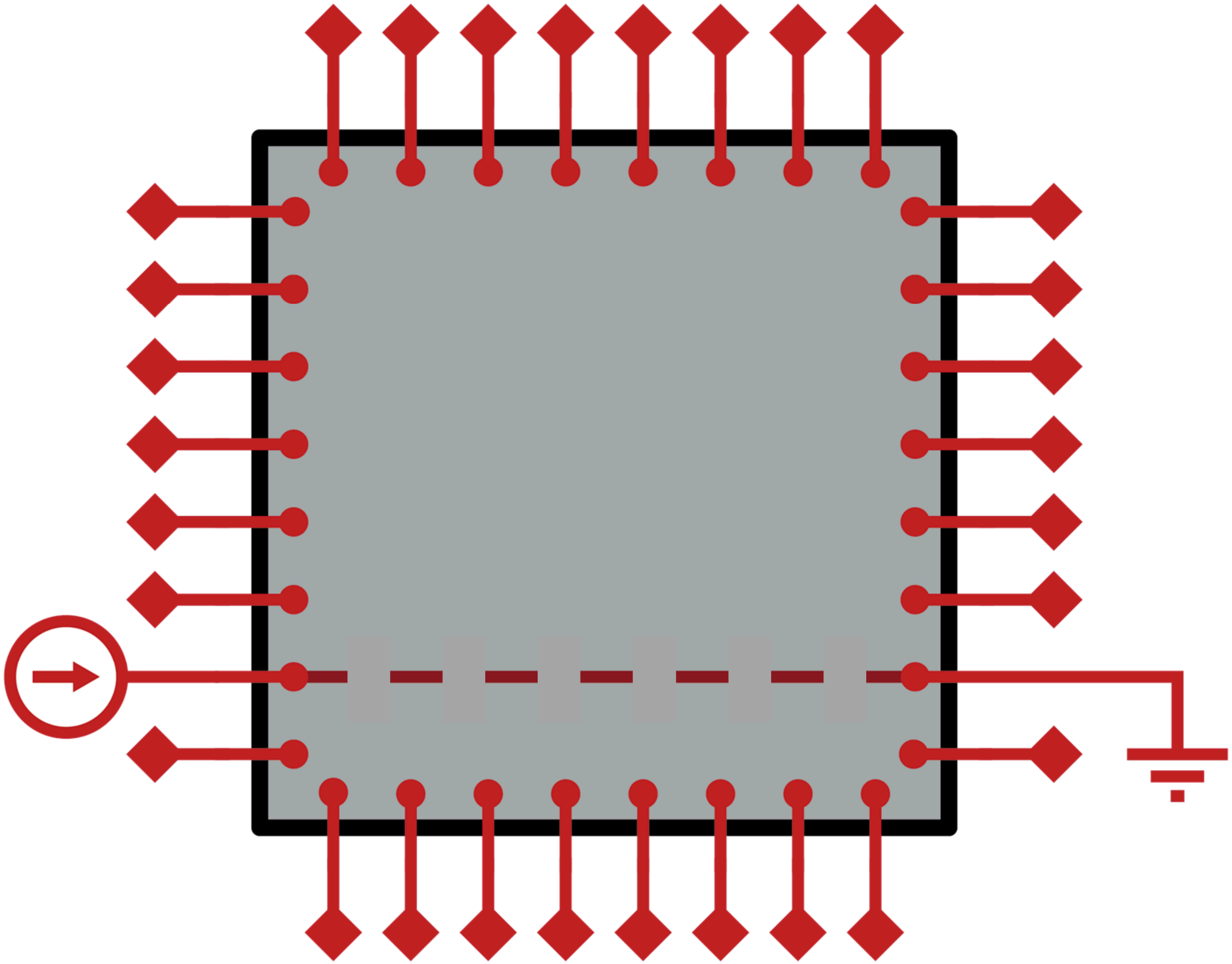
EIT Measurements



EIT Measurements



EIT Measurements

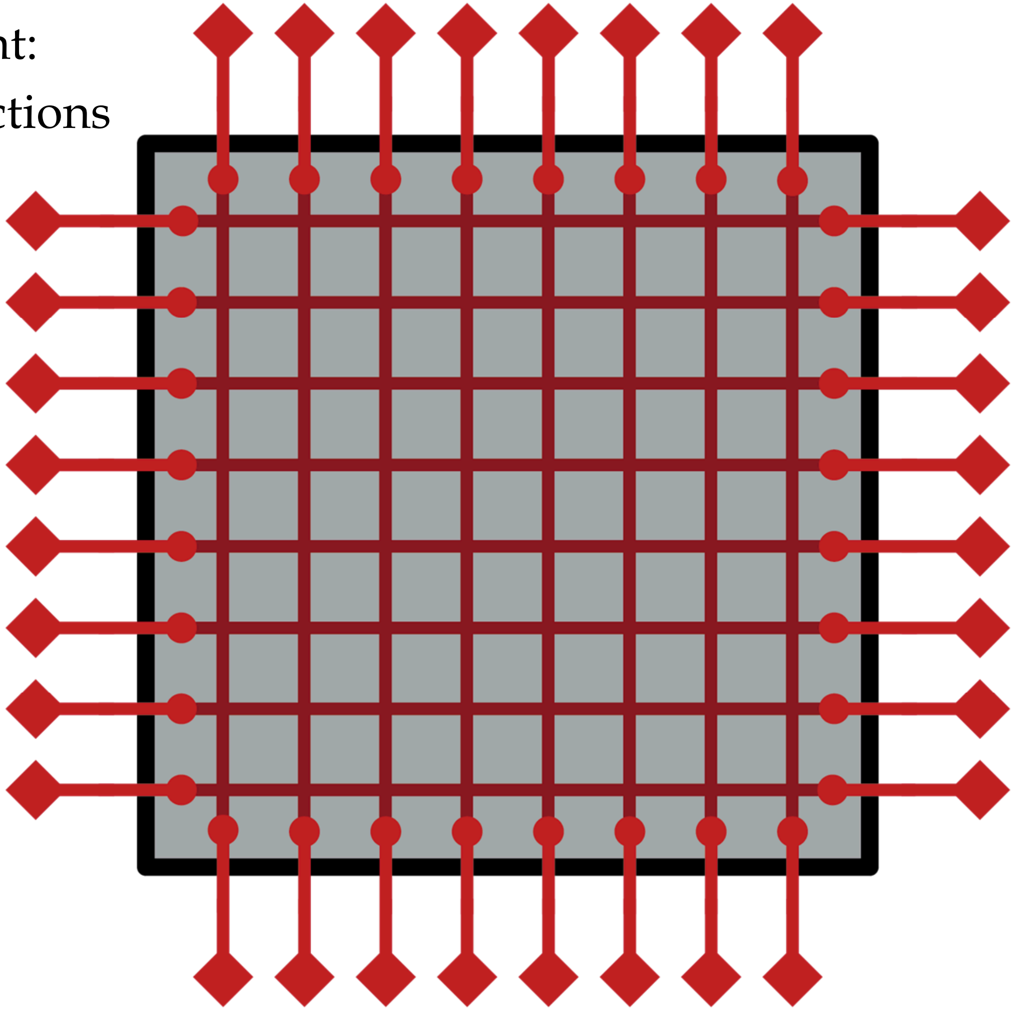


EIT Measurements

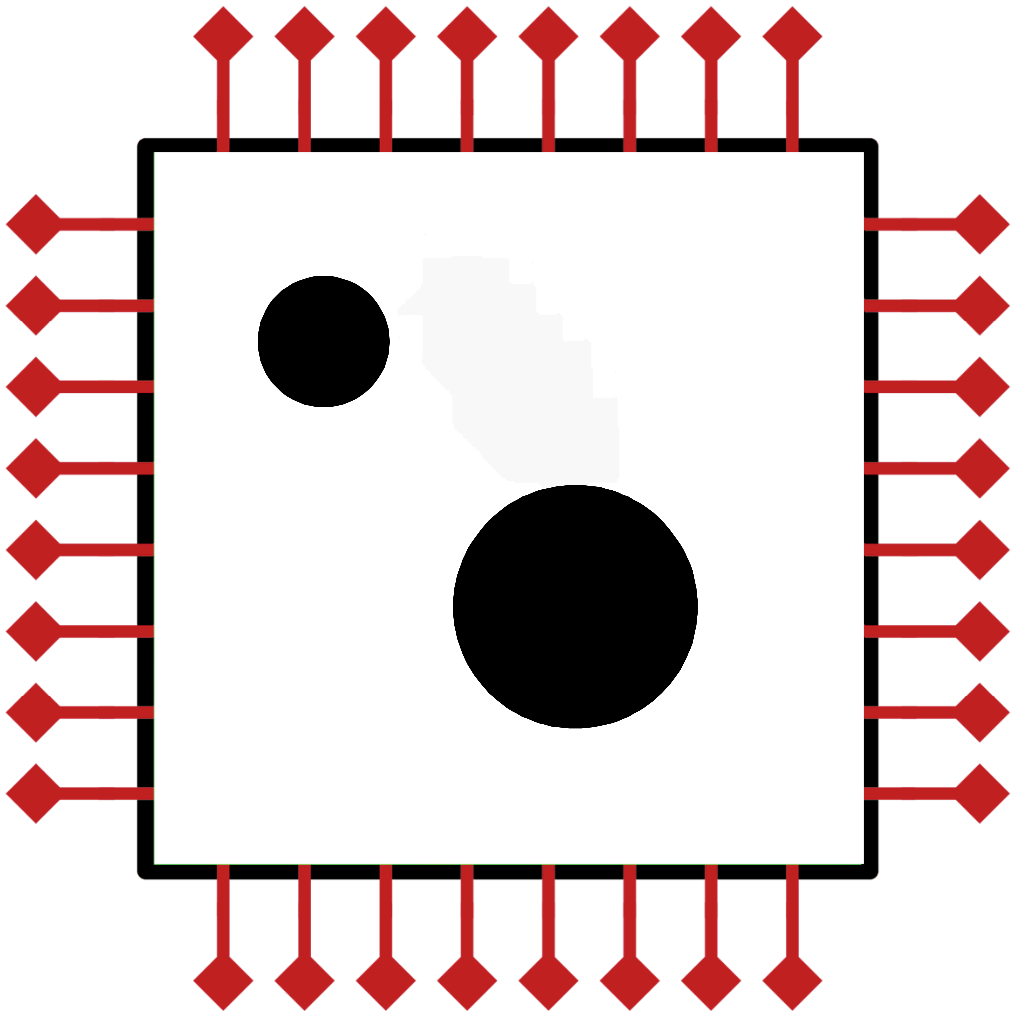
EIT Measurement:

32 current injections
x 32 nodes

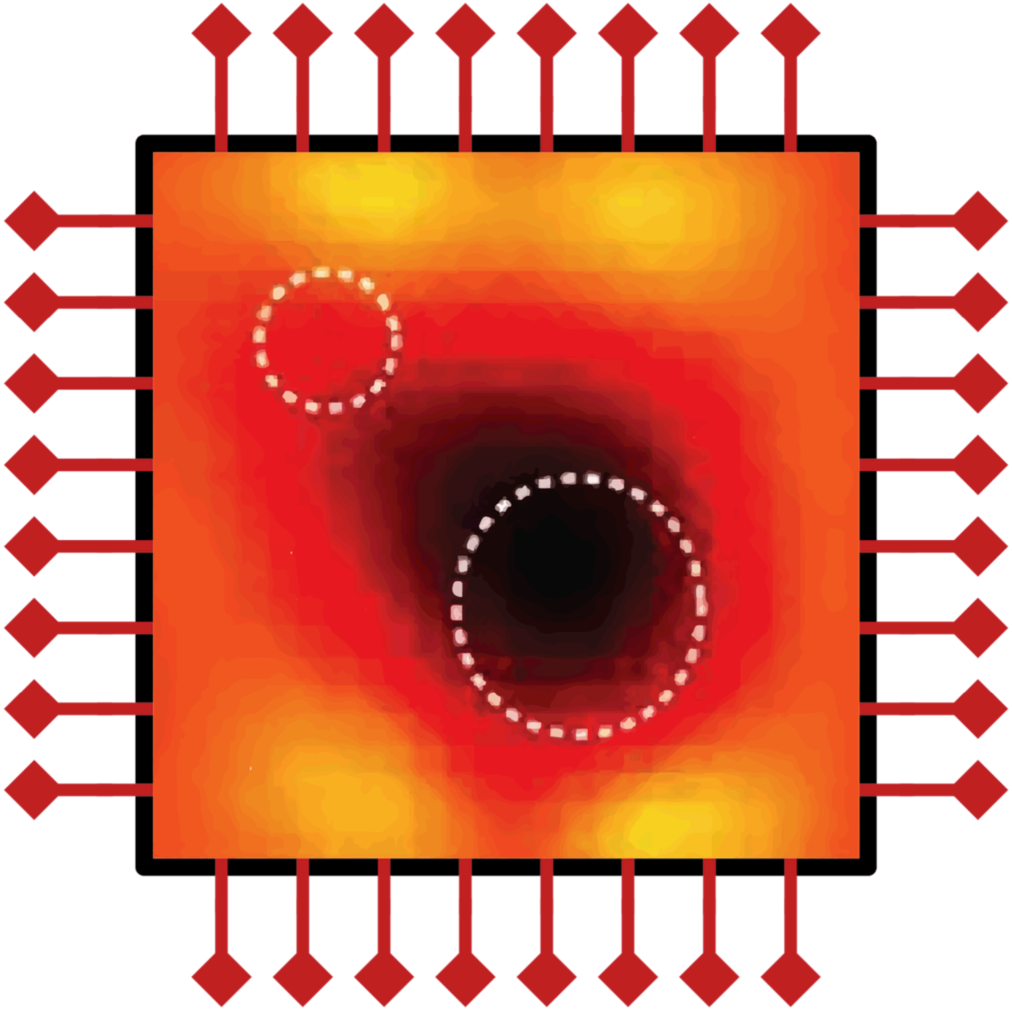
1024 voltage measurements



EIT Measurements

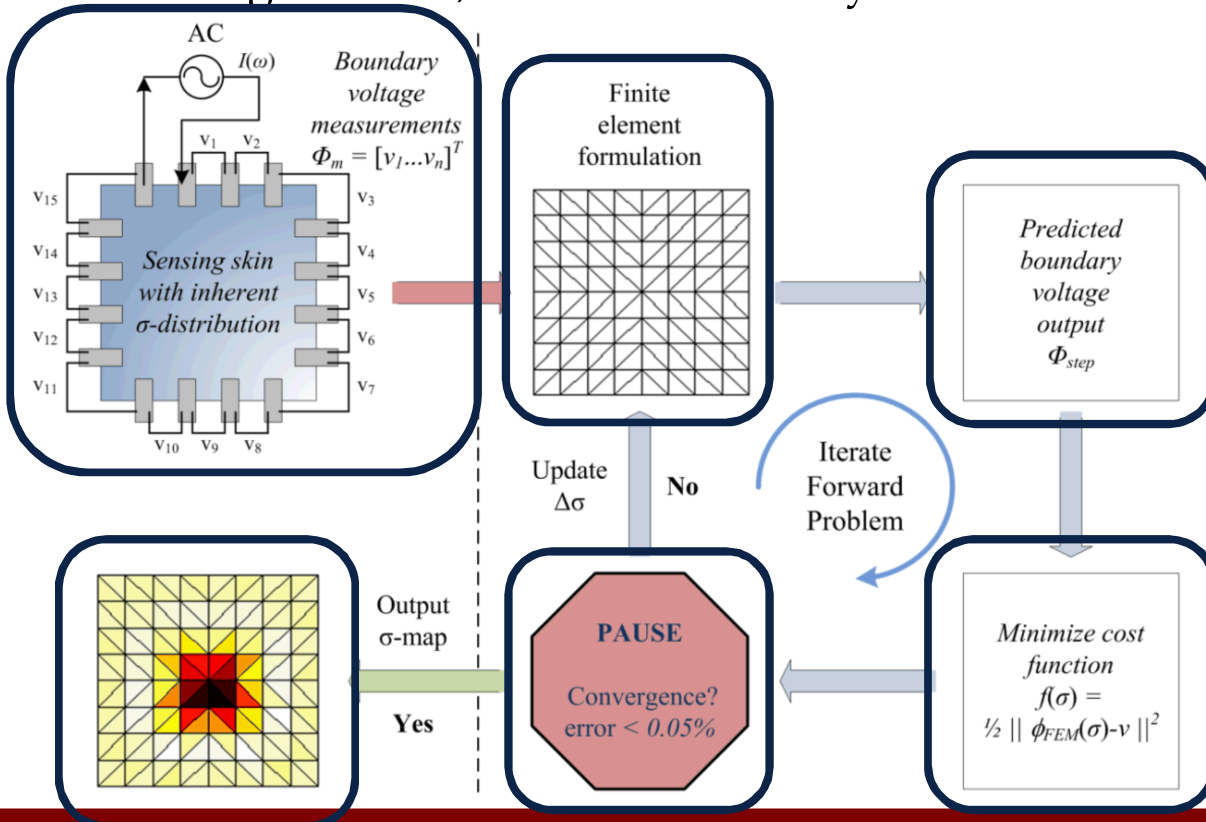


EIT Measurements



Typical EIT Reconstruction

- Laplace's equation:
  - $\nabla \cdot (\sigma \, \nabla \phi) = 0$, where σ can vary by orders of magnitude
  - Governs potential and conductivity relationship
- Forward problem: conductivity known, solve voltage
- Inverse problem: voltage known, solve conductivity



Linear EIT Reconstruction

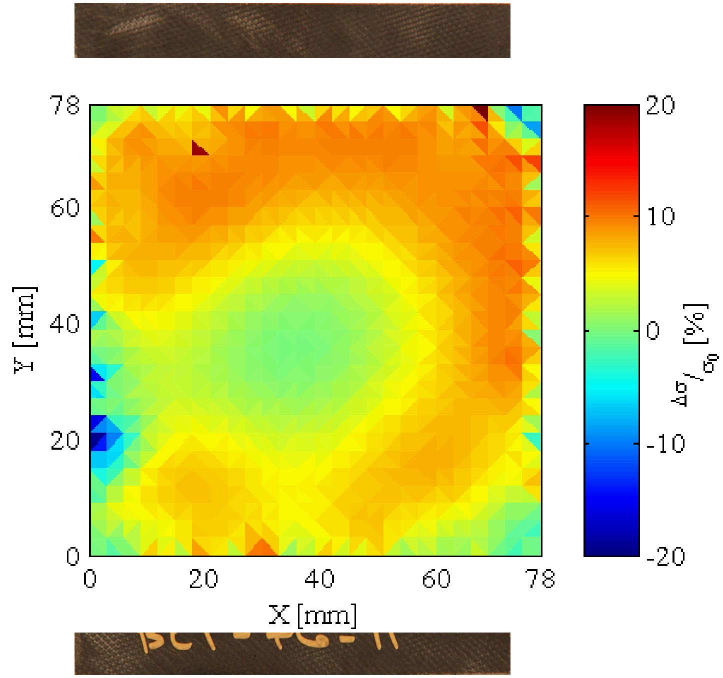
$$\frac{\Delta\sigma}{\sigma_0} = \left(\underline{H}^T W \underline{H} + \lambda \underline{R}\right)^{-1}\left(\underline{H}^T W\right)\frac{\Delta V}{V_0}$$

$$\frac{\Delta\sigma}{\sigma_0} = B\Delta\frac{\Delta V}{V_0}$$

- Reconstructs small σ changes:
  - Typically difference imaging
    - $\sigma_1 - \sigma_2 << \sigma_2$
- Maximum a posteriori (MAP):
  - H: sensitivity matrix

    $$H\left(\sigma_{bkgd}\right)_{ij} = \frac{\partial V_i}{\partial \sigma_j}$$
  - Regularization hyperparameter: λ
    - Noise figure

      $$NF(\lambda) = \frac{SNR_{in}}{SNR_{out}} \approx 1$$
    - Use representative σ distribution
  - W: Noise model
  - R: Regularization matrix
- Advantages:
  - Can pre-calculate H
  - Many damage modes lead to small changes in σ



Applied Spatial Sensing

Spatially Distributed Sensitivity

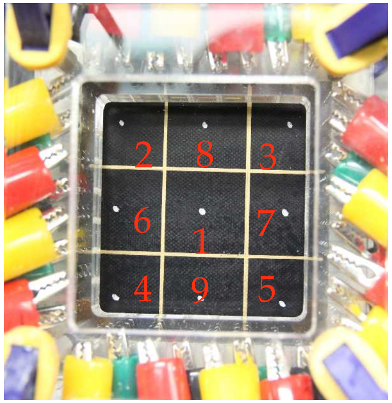
- Understand sensitivity to prescribed damage w.r.t. spatial position in sensing area
- 9 holes distributed across specimen
- 6.35 mm diameter

Spatially Distributed Strain Sensitivity

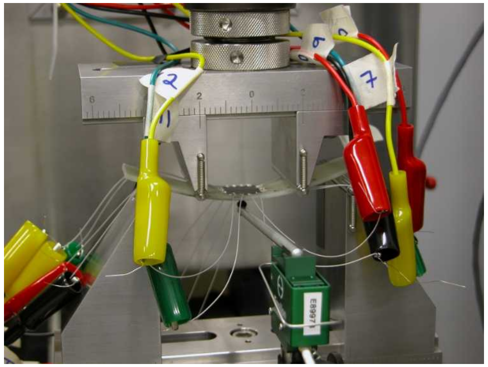
- 4-pt bending specimens
  - Homogeneous strain between inner supports
- Tensile and compressive strain values
- Small changes in conductivity

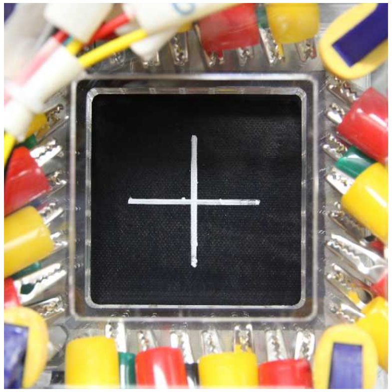
Damage Size Sensitivity

- Understand sensitivity to increasing damage at center of specimen
- Least sensitivity point in sensing region
- 6 progressively larger holes
  - $^1/_{16}$", $^1/_{8}$", $^3/_{16}$", $^1/_{4}$", $^5/_{16}$", $^3/_{8}$"



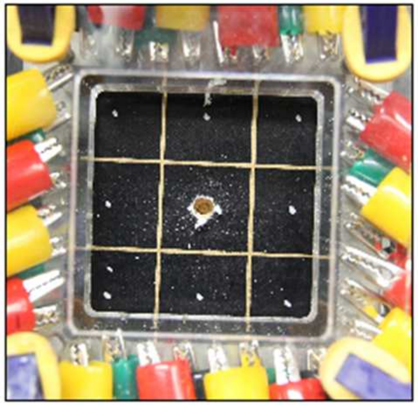
Spatially Distributed Sensitivity Specimen


Spatially Distributed Strain Sensitivity Specimen

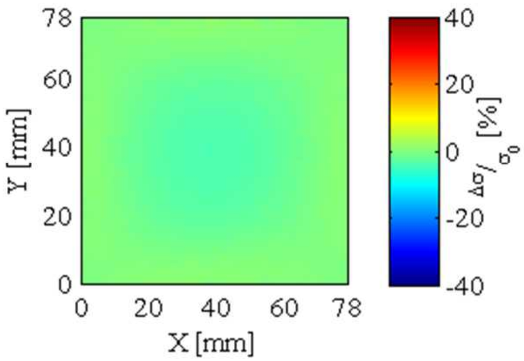

Damage Size Sensitivity Specimen

Spatially Distributed Sensitivity

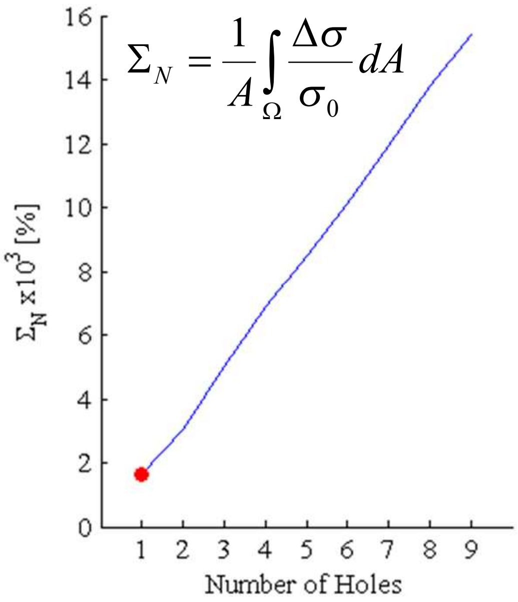
- EIT Response
  - Consistent cumulative amplitude response
    - Linear response to increasing sustained damage
  - Further from center, response more disperse
    - Mean response at correct damage location



Specimen



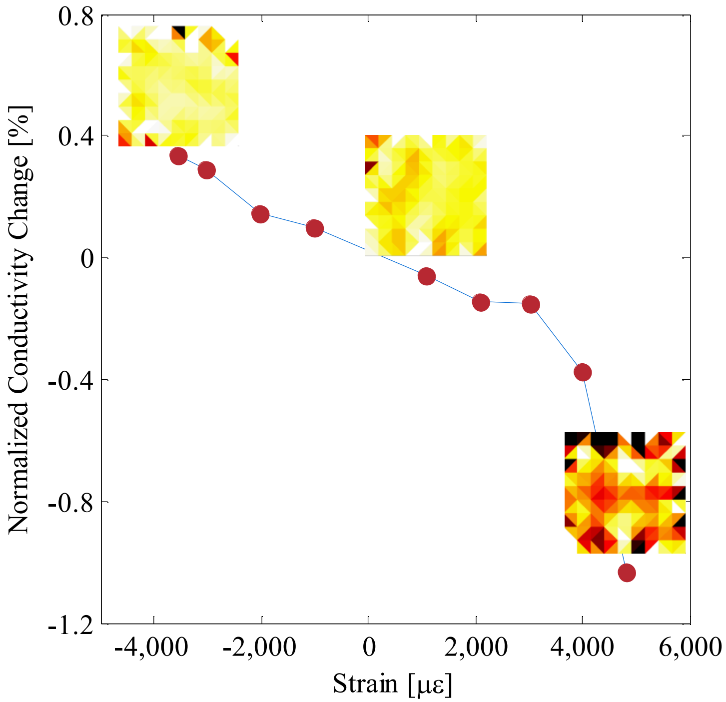
EIT Response

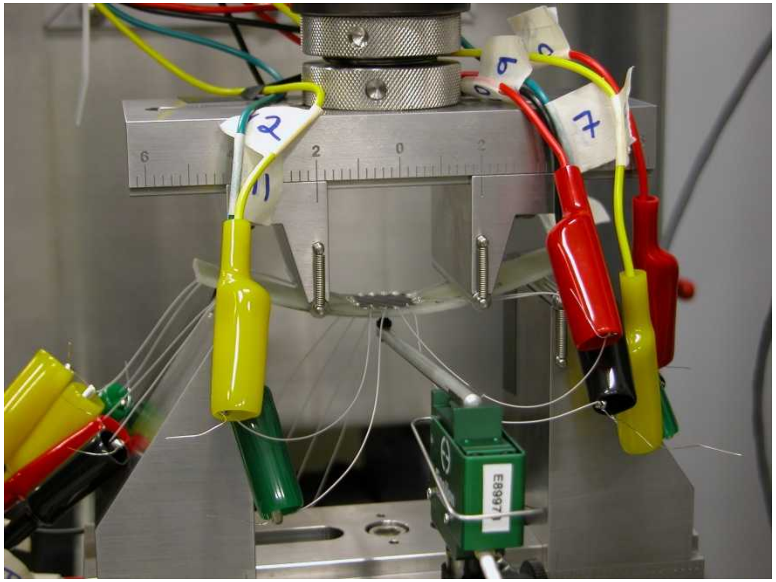


Damage Metric

Spatial Strain Sensing

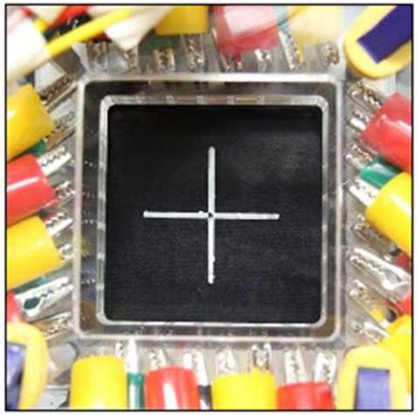
- 4-pt bending
  - **ASTM D7264**
  - MWNT-Latex on GFRP
  - Stepped displacement profile
  - Tensile/compressive strain
- Strain sensitivity
  - Nearly linear



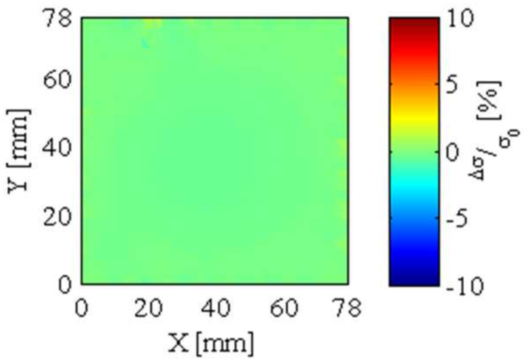


Damage Size Sensitivity

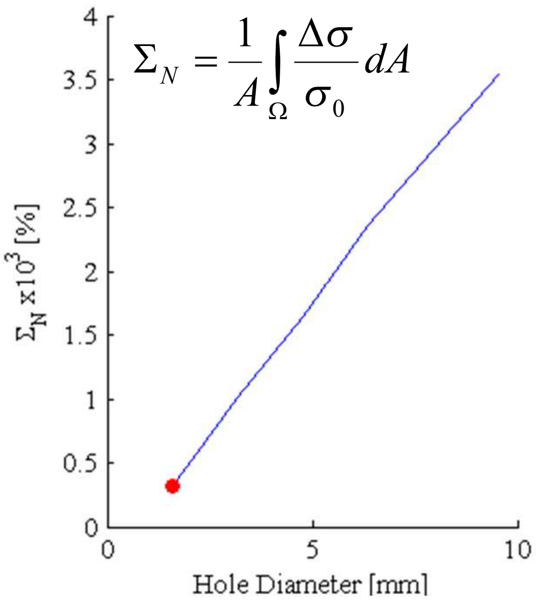
- EIT Response
  - Increasing EIT response to increasing damage size
    - Nearly linear response to size
  - EIT response at corresponding location to damage but response size is exaggerated



Specimen



EIT Response



Damage Metric

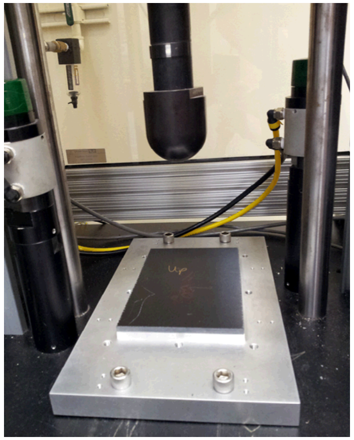
Impact Damage Detection

Sandia National Laboratories

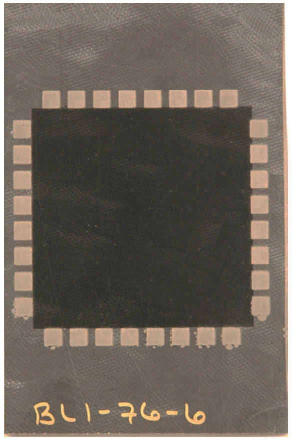
- Drop-weight impact tests
  - **ASTM D7146**
  - 78 mm by 78 mm sensing region
  - MWNT-latex on glass fiber weave
  - Impact energy: 20, 60, 100, 140 J
  - Before/after EIT measurements

- Verification:
  - Photographic Imaging
    - Surface damage

Drop-weight impact tester



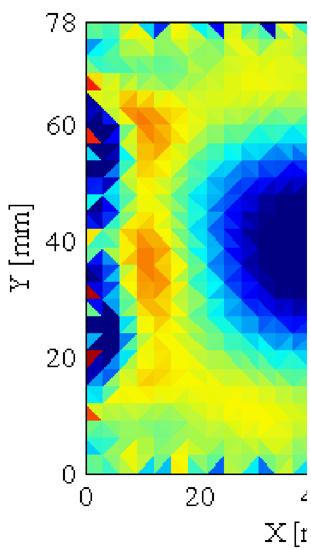
Impact setup



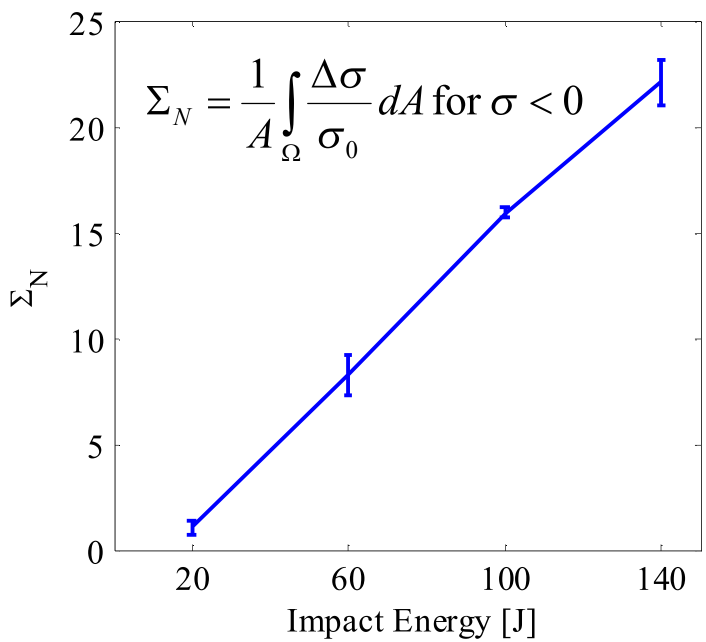
Impact specimen

Impact Damage Detection

- EIT reconstruction captures conductivity decrease in damaged region
  - Decreasing amplitude and increasing response region with increase in impact energy
- Linear response w.r.t. damage metric with good repeatability



EIT Response

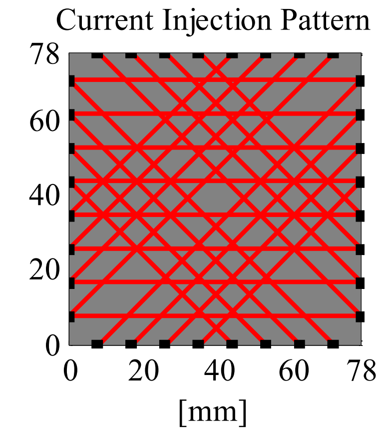


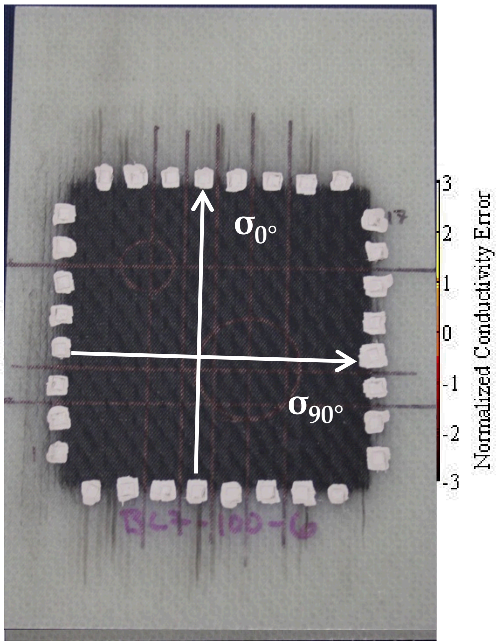
Plot of the damage metric versus impact energy

Opposite face of impacted specimen

Embedded Spatial Sensing

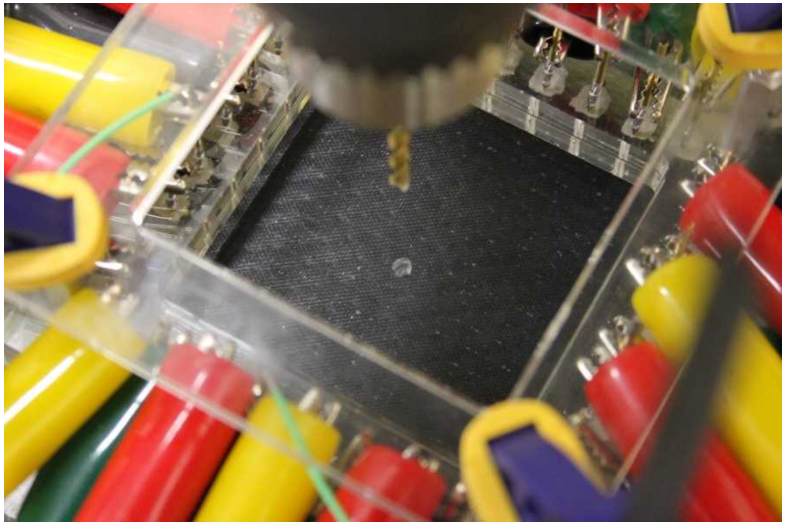
- Embedded sensing architecture
  - MWNT-Latex on GF fiber weave
  - Embedded within epoxy matrix
- Specimens
  - $[0^o/+45^o/90^o/-45^o]_{2s}$
  - Unidirectional GF
  - 150 mm x 100 mm
    - ASTM D7146 Standard
- Anisotropic EIT
  - Isotropic ▸ Anisotropic
  - Scalar ▸ Matrix: σ
  - $\sigma_{0^\circ} > \sigma_{90^\circ}$ by ~2:1
  - $\nabla \cdot (\sigma \nabla \phi) = 0$

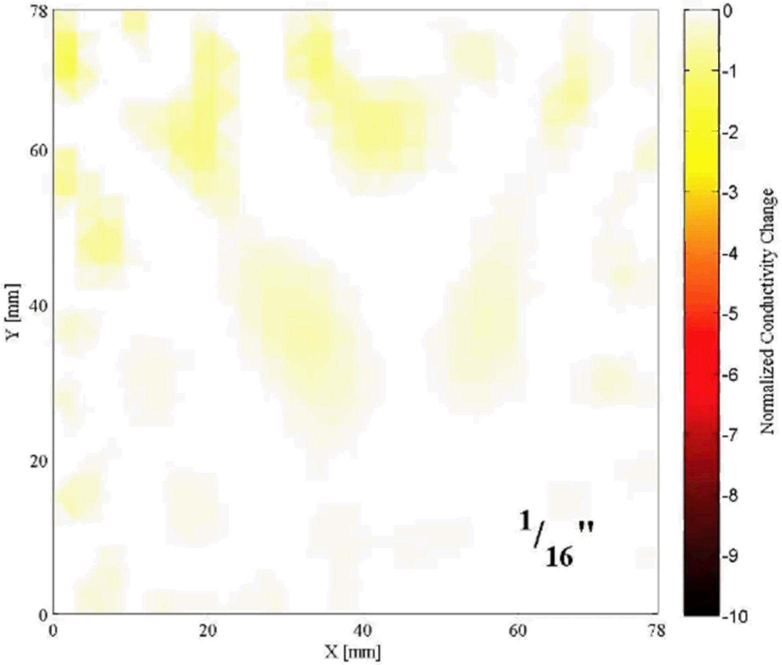




Embedded Spatial Sensitivity

- Embedded sensing validation:
  - Determine conductivity change sensitivity
  - Process:
    - Progressively larger drilled holes:
    - $^1/_{16}$″, $^1/_8$″, $^3/_{16}$″, $^1/_4$″, $^5/_{16}$″, $^3/_8$″, $^1/_2$″
  - Anisotropic EIT performed
    - Conductivity change from pristine sample



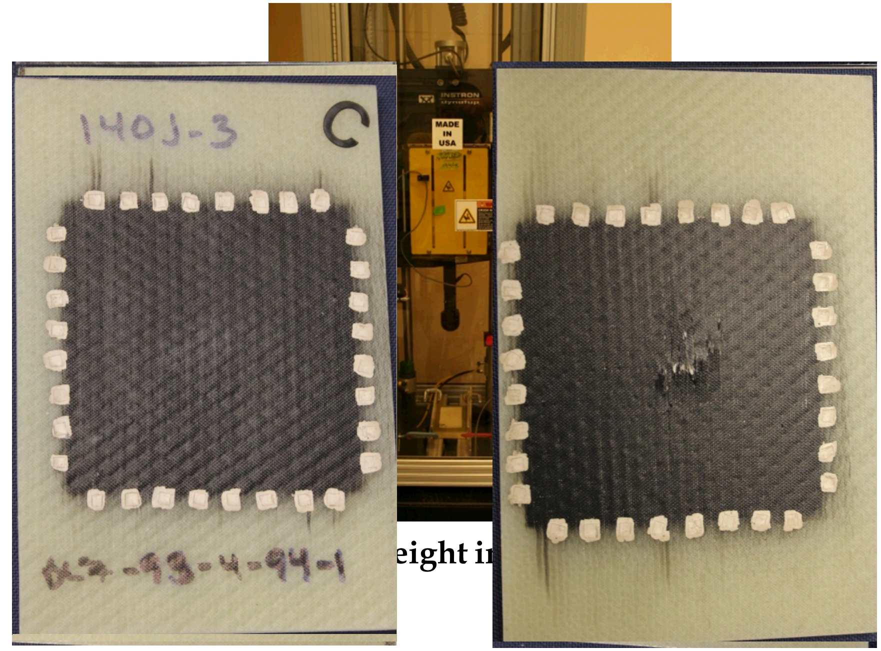


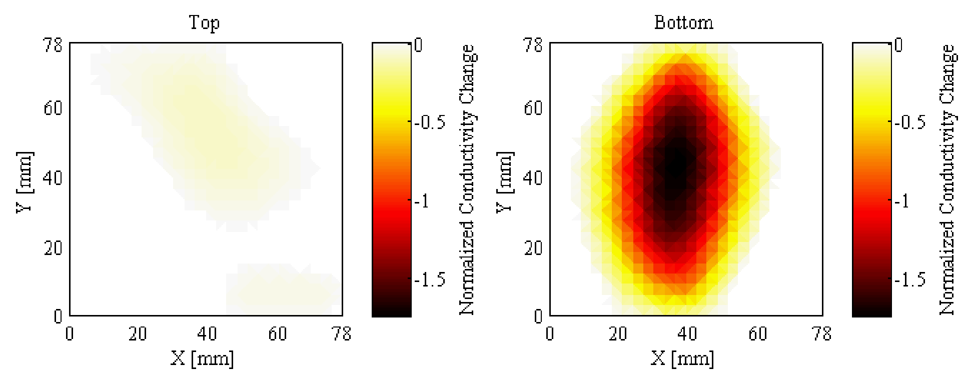
Impact Damage Detection

Sandia National Laboratories

- Drop-weight impact tests
  - **ASTM D7146**
  - 78 mm by 78 mm sensing region
  - MWNT-latex on glass fiber weave
  - Impact energy: 20, 60, 100, 140 J
  - Before/after EIT measurements

- Verification:
  - Thermography
    - Matrix Cracking
    - Delamination
  - Photographic Imaging
    - Surface damage





EIT DAQ System and the Utah Clinic

Sandia National Laboratories

Original DAQ Design

- 90 seconds/EIT measurement
  - 11 voltage measurements/sec.
- ~$9,500
- 430 in^2 (~50 lbs)
  - Difficult to scale

Senior Design Project Goals

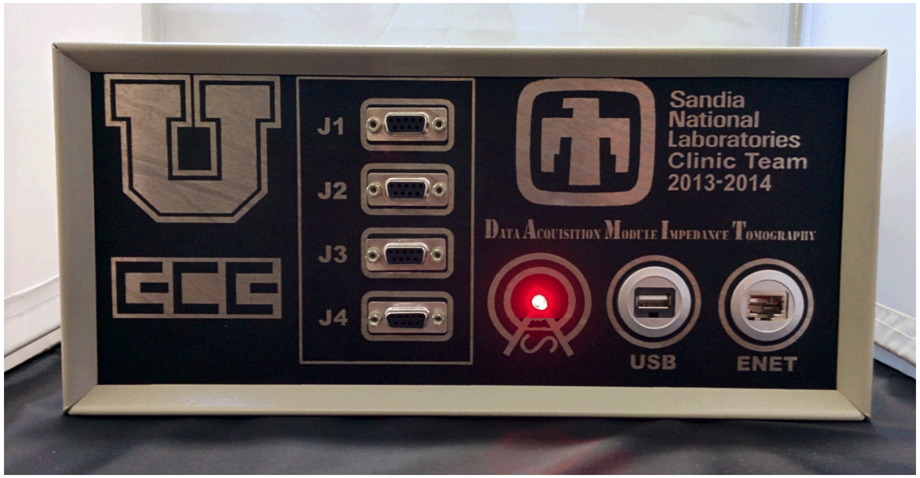
- 100 EIT measurement/sec.
  - 100k voltage measurements/sec.
- Modular (+32 nodes)
  - Unit cost < $1,000
- Graphical User Interface (GUI)
  - User defined current injection pattern
- Adjustable current source between
  1 µA to 100 mA
- Enclosure – field testing
- Project budget: $3,000

Agilent digital multimeter
Keithely current source
Agilent multifunction switch/measure unit

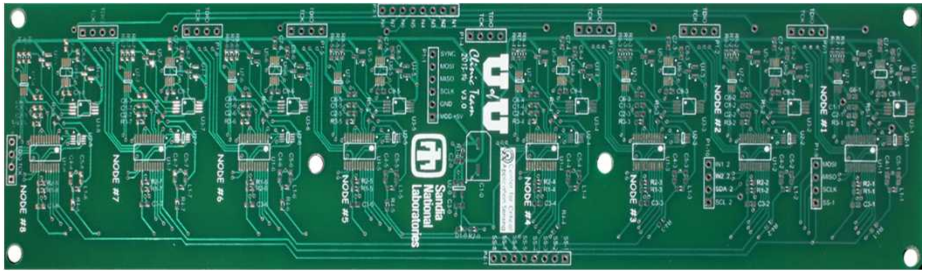
Utah Clinic 2013-2014

Sandia National Laboratories

- Version "0"
- 32 node design
  - Completely parallel system
  - Each node:
    - Current source
    - Ground
    - ADC for voltage measurement
- Speed: Never tested
- Cost: ~$1300



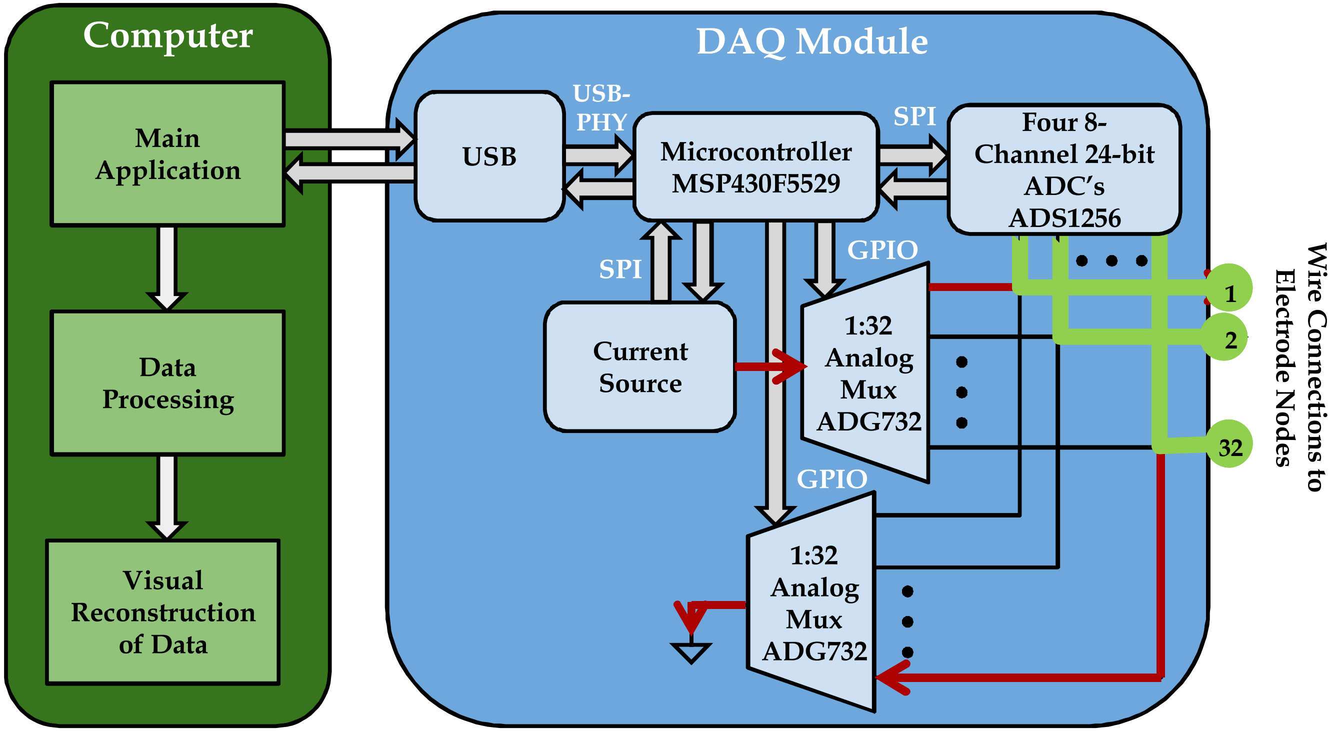
EIT DAQ in Aluminum Enclosure



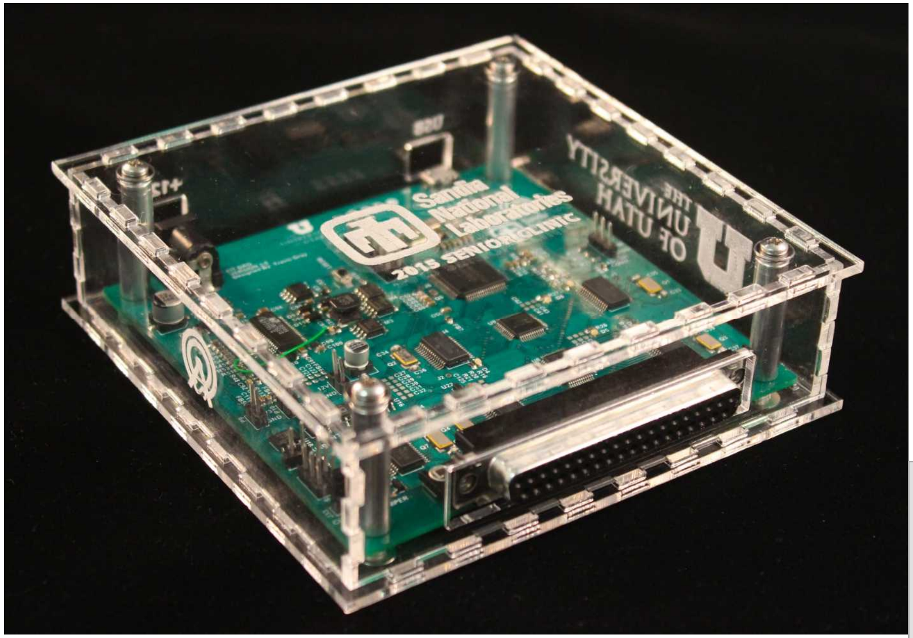
EIT DAQ PCB Board (1 of 4)

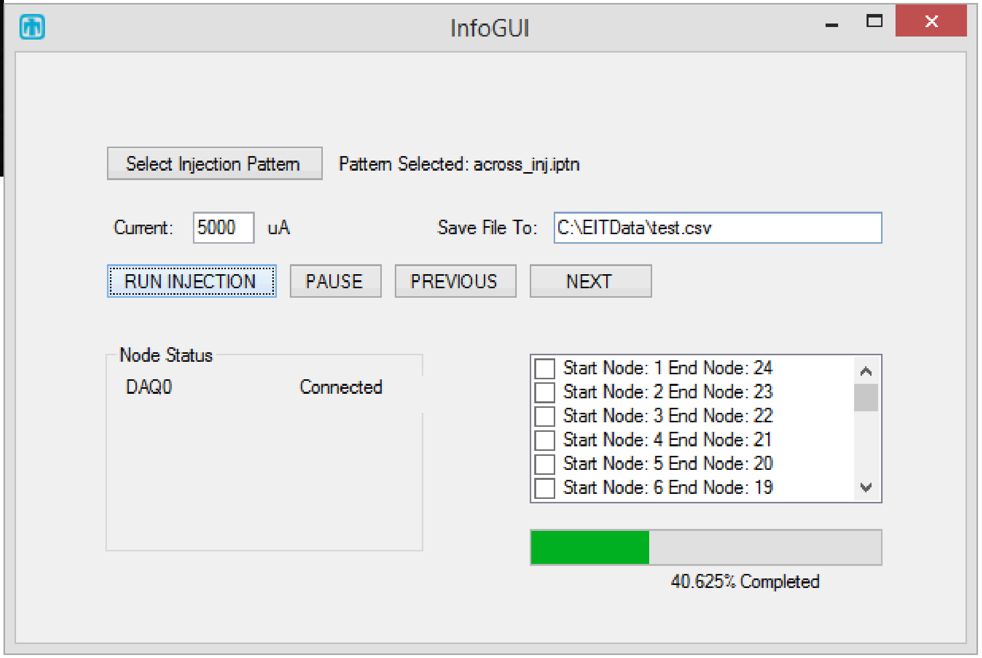
Utah Clinic 2014-2015

- Versions: 1 and 2
- Multiplexed design
  - 32 nodes per DAQ
  - Ground and current injection set to assigned electrodes
  - Voltage measurements are multiplexed amongst remaining nodes
- Up to 8 DAQs can be connected to each computer
  - Up to 256 nodes
- Speed: 1.8s per EIT measurement
- Cost: $422



Utah Clinic 2014-2015



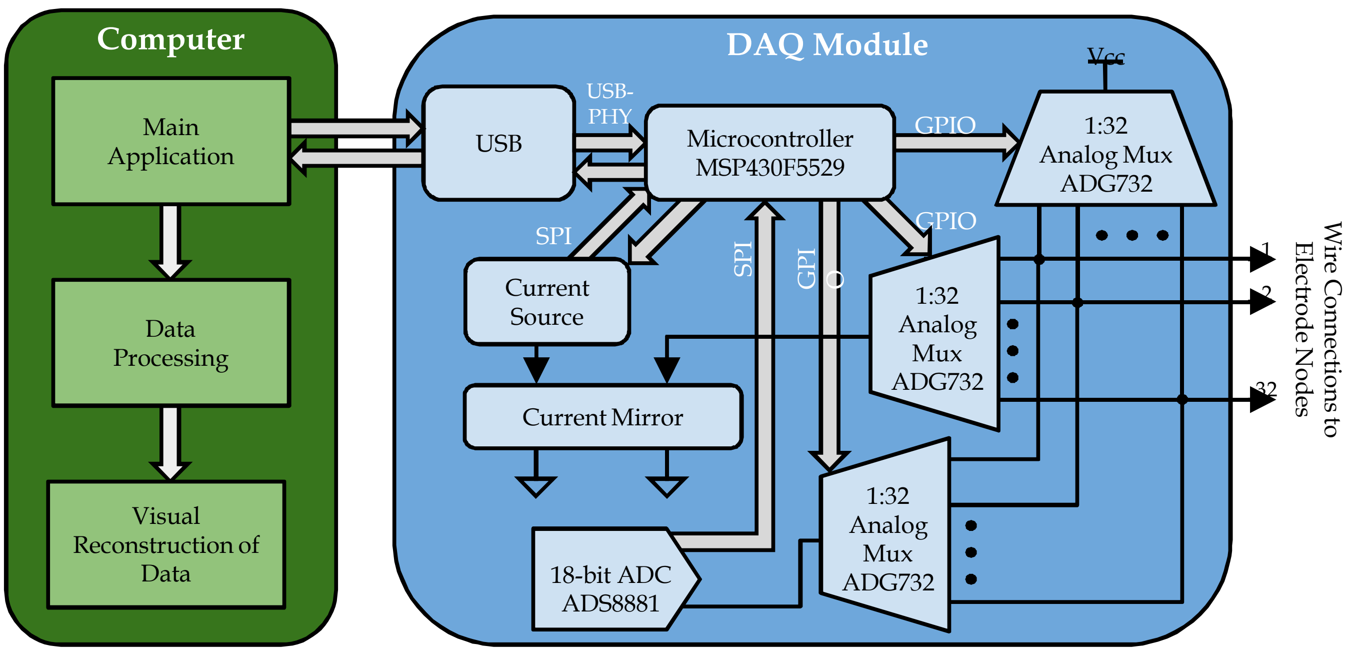


Summer Internship 2015

Sandia National Laboratories

- Versions: 3.0, 3.1, 4.0, and 4.1
- Updates:
  - Lower noise voltage measurements
  - Smaller footprint
  - Lower power
  - Improved design for speed

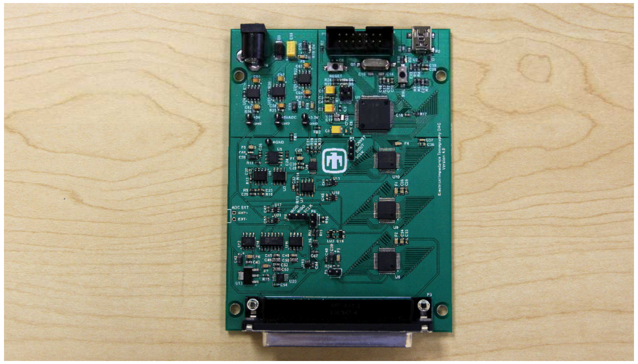
Version	Supply	Ripple ($V_{pk\text{-}pk}$)	Noise (V_{rms})
3.0	5 V	230 mV	43 mV
	3.3 V	19.9 mV	3.45 mV
3.1	5 V	3.55 mV	1.55 mV
	3.3 V	2.93 mV	827 uV

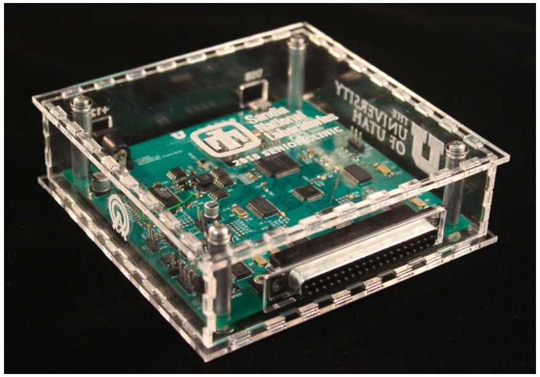


Version Comparisons

Sandia National Laboratories

	Version 4.0	Version 3.0	Original Setup
EIT Measurement	est. 1 ms	1.8 sec.	90 sec.
Voltage Measurements	est. 100k per sec.	11.2k per sec.	11.4 per sec.
Unit Cost	$252	$422	~$9,500
Current Source	est. 10uA – 100mA	10uA – 10mA	100fA – 105mA
GUI	Yes	Yes	No
Area Footprint (Weight)	15 in^2 (<1 lb)	16 in^2 (<1 lb)	430 in^2 (~50 lbs)
Communication	USB	USB	USB
Power	est. 0.6 W	0.5 W	+10W





Thank You!

Sandia National Laboratories

Questions?

Acknowledgements:

National Institute for Nano Engineering (NINE)

Center for Critical Application Sensing

UC DAVIS OFFICE OF GRADUATE STUDIES

CITRIS Center for Information Technology Research in the Interest of Society

National Science Foundation WHERE DISCOVERIES BEGIN