Self-powered Wireless Sensors for Monitoring the Electric Power Grid

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Outline

- Introduction/Motivation
- Wireless MEMS Sensor Module concept
- MEMS Proximity Sensing
- AC Energy Scavenging
- Conclusion

Acknowledgements

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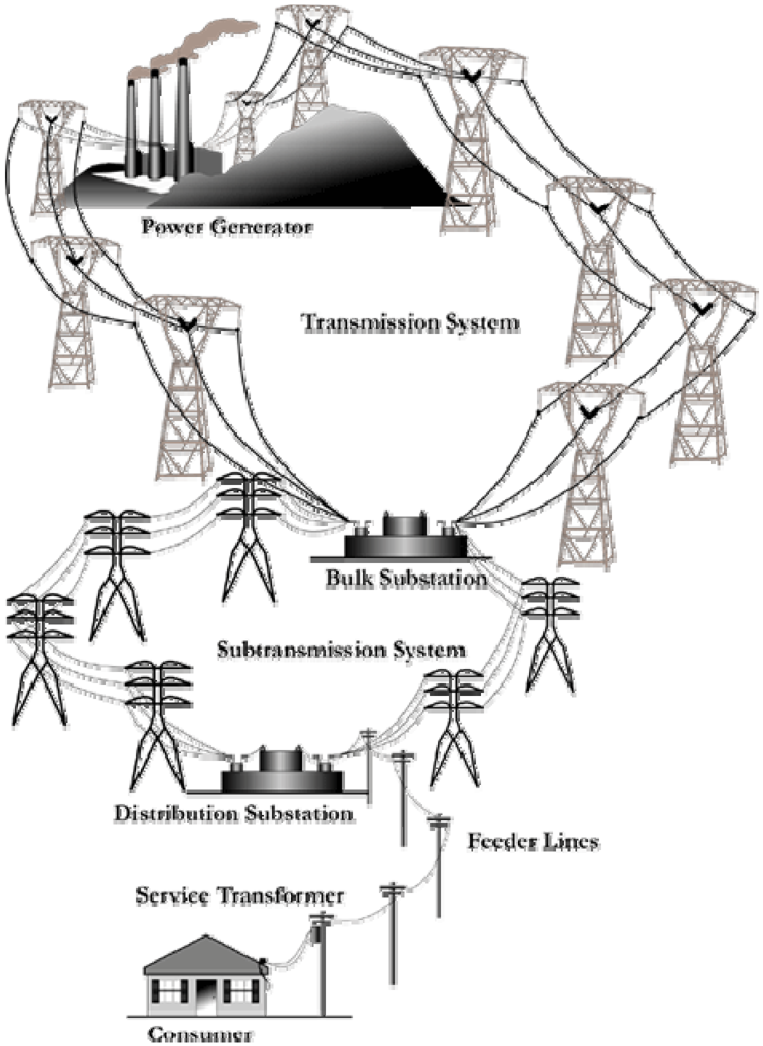
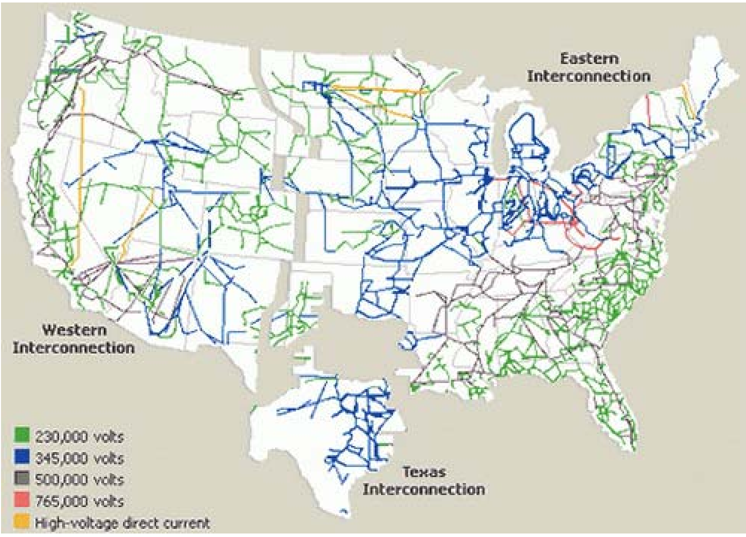
The U.S. Power Grid



Congressional Budget Office

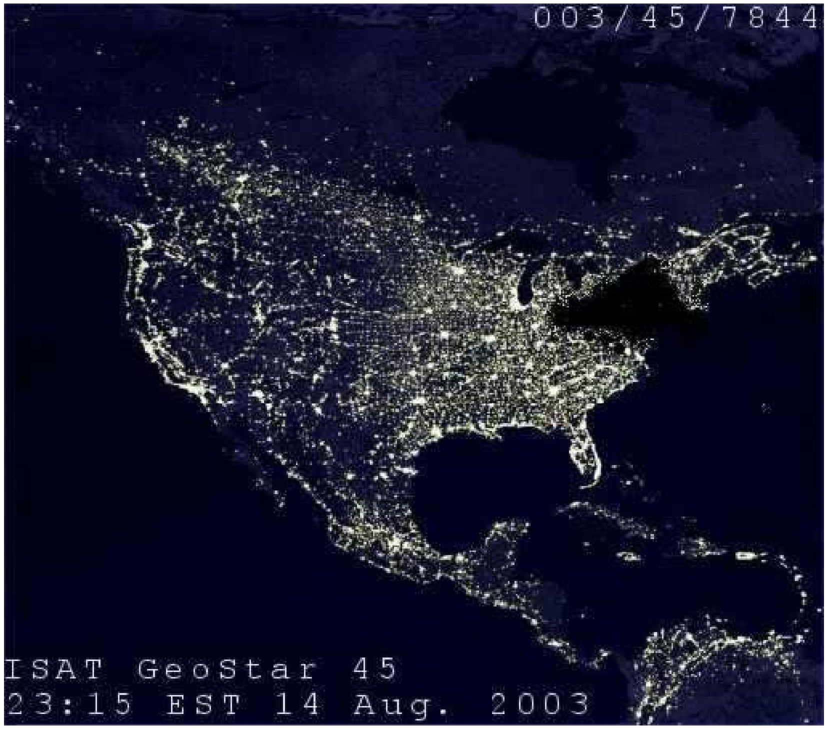
- Largest interconnected machine on Earth
- Contains:
  - 9,200 generating units
  - 1,000,000 MW capacity
  - 300,000 miles of transmission lines

Department of Energy



Device Daily . com

Upcoming Challenges



Northeast Blackout of 2003
Estimated Loss = $6 B

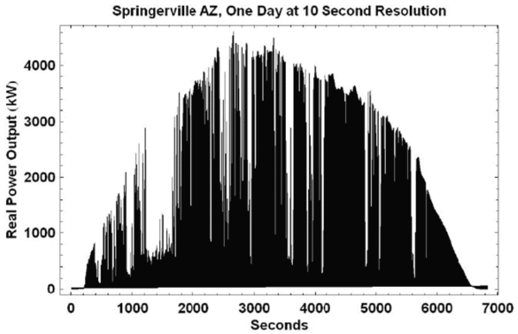
- Increasing number of outages:
  - A 126 % increase in non-disaster related blackouts affecting at least 50,000 customers
    - 41 (1991-95) – 92 (2001-05)
    - 36 in 2006 alone!

U.S. electricity blackouts skyrocketing, CNN, Aug. 9, 2010

- Reduced Transmission $$'s
  - $5 B in 1975
  - $2.5 B in 2000

Department of Energy

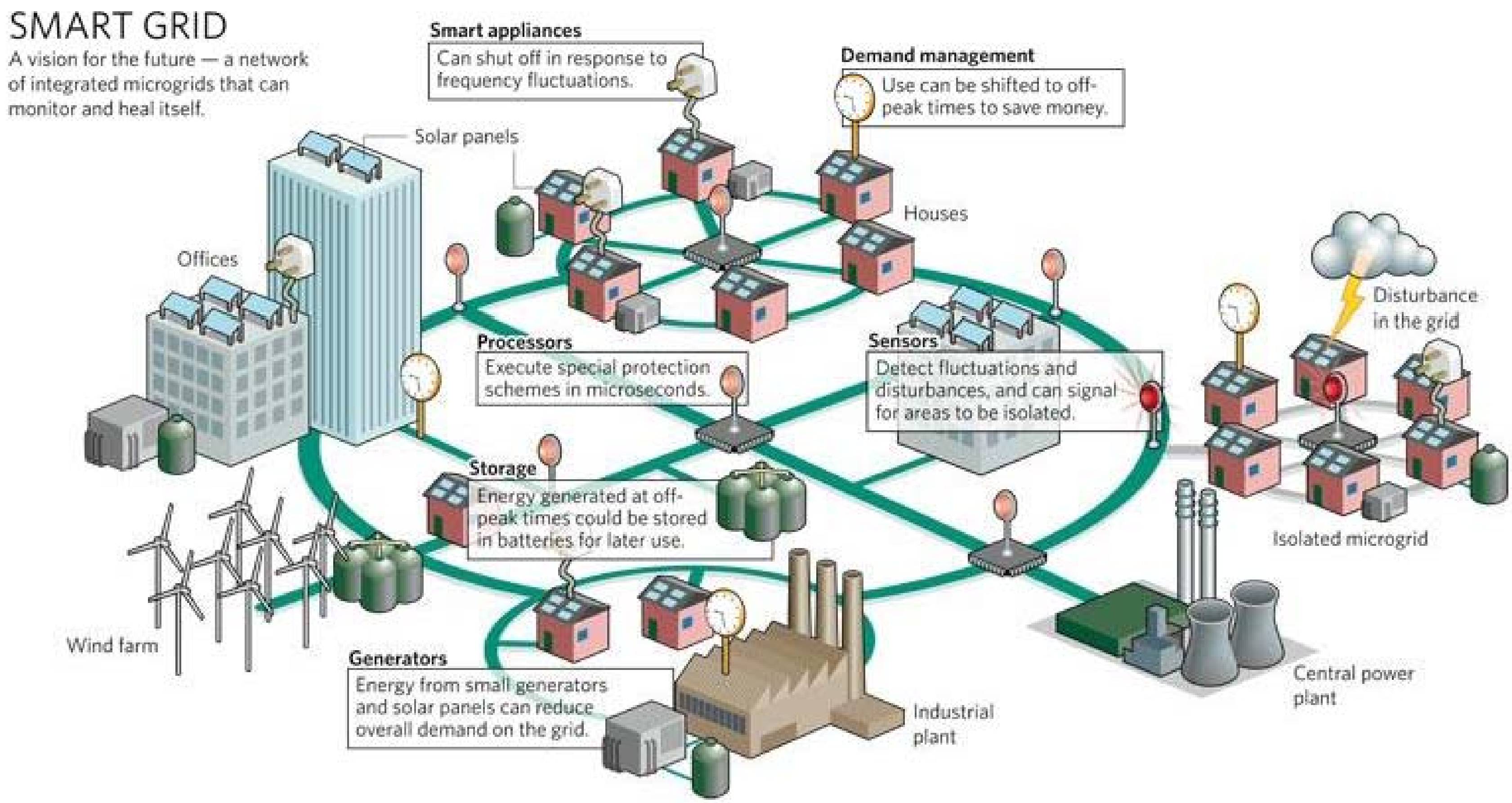
- Renewable Energy Penetration



Example daily solar power output

Carnegie Mellon Electricity Industry Center

The New "Smarter" Grid



Consumer Energy Report

Smart Grid – opportunity for MEMS

- Smart Grid = the need for many sensors
  - PG&E alone estimate the need for 900,000 sensors
    - 15 million customers = 1 sensor /15 people
  - CA - 2.2 million units
  - U.S. – 19 million units

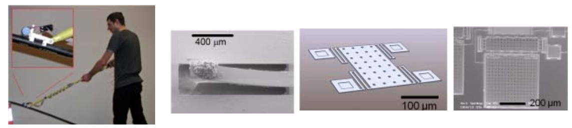
- Present voltage/current sensing technologies:
  - State of the art: $3,000 per - 3-phase test point
  - Clamp-on meters: $100 - $200 per phase
  - Wireless solutions: ~ $75 per phase
  - Low-end sensor: $21.99 residential sub-metering

MEMS Power Systems Sensing

- Project one-two order of magnitude lower cost
    - Batch processing
    - Wafer-level integration
    - Novel materials
- Reduce installation cost
    - Small, easy to install (stick-on)
    - Can be embedded in new equipment
- Self-powered
    - Low-power MEMS sensors and radios
    - Longevity

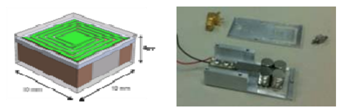
Imagine the possibilities !

Our Self-Powered Wireless MEMS Sensor Module Concept



- AC Current
- Voltage
- Power
- Diagnostic

MEMS Proximity Sensing

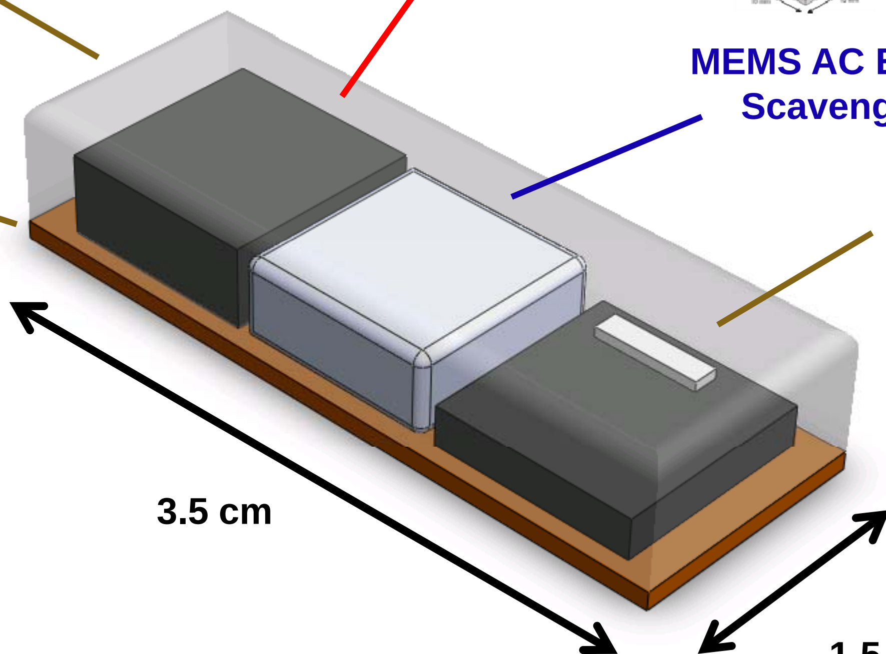


- MEMS Design
- Mesoscale

MEMS AC Energy Scavenging

Hermetic (wafer level) packaging

(Printed) Energy storage



3.5 cm

1.5 cm

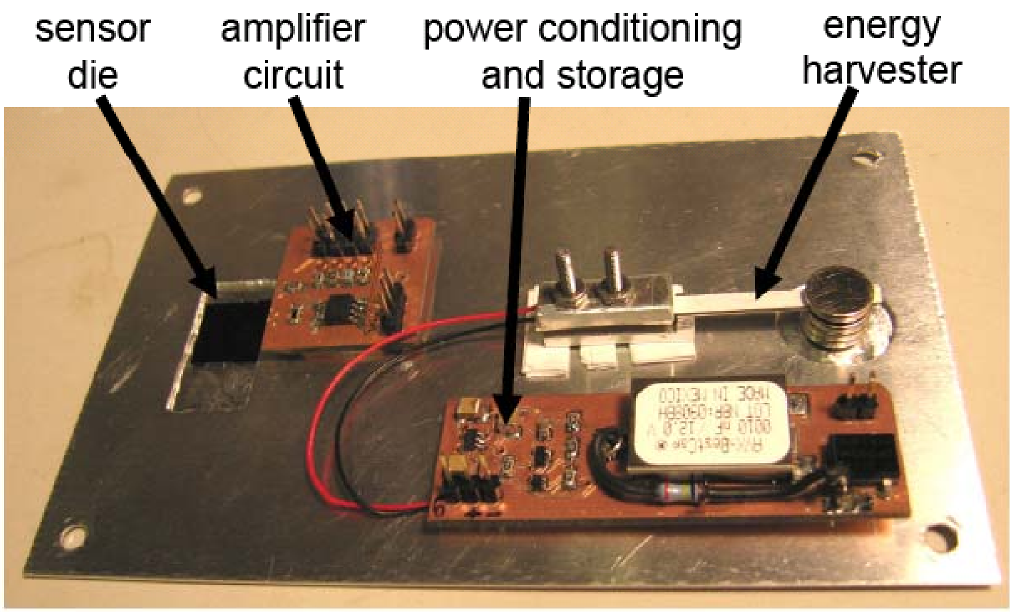
Radio Mote

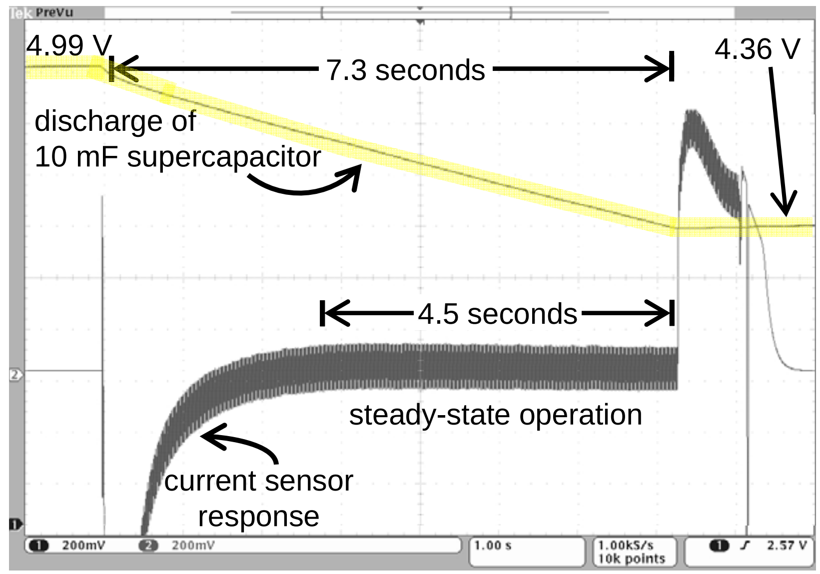
- Low-power wireless mesh network
  - TI eZ430-F2013
  - Dust networks
  - Pico cube
  - IEEE 802.15.4 protocol

V. 2.0

Paprotny et al, ECCE 2010

Self-Powered Wireless Sensor Module V 1.0





Leland E.S., Sherman C.T. , Minor P., Wright P.K., and White. R.M. PowerMEMS 2009
Leland E.S., Sherman C.T. , Wright P.K., and White. R.M. tSensors 2010

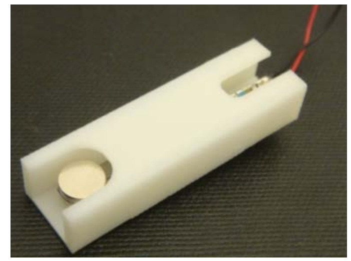
Long term Goal

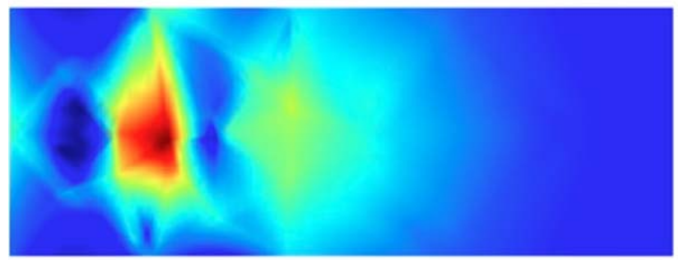
Ubiquitous Power Systems Sensing

- Inexpensive power/voltage/diagnostic power systems sensors that are distributed throughout our homes
  - Embedded from the start (e.g., starting to happen with smart appliances)
  - Easy to retrofit
    - For example Sticky-tab meter

- Applications include (but not limited to):
  - Modules that measure flow of power in the grid (V 2.0)
  - Underground cables that report on their condition (V 2.0)
  - Appliances extension cords that report power usage (V 3.0)
  - Wireless “sticky tab” wireless electric meters (V 4.0)

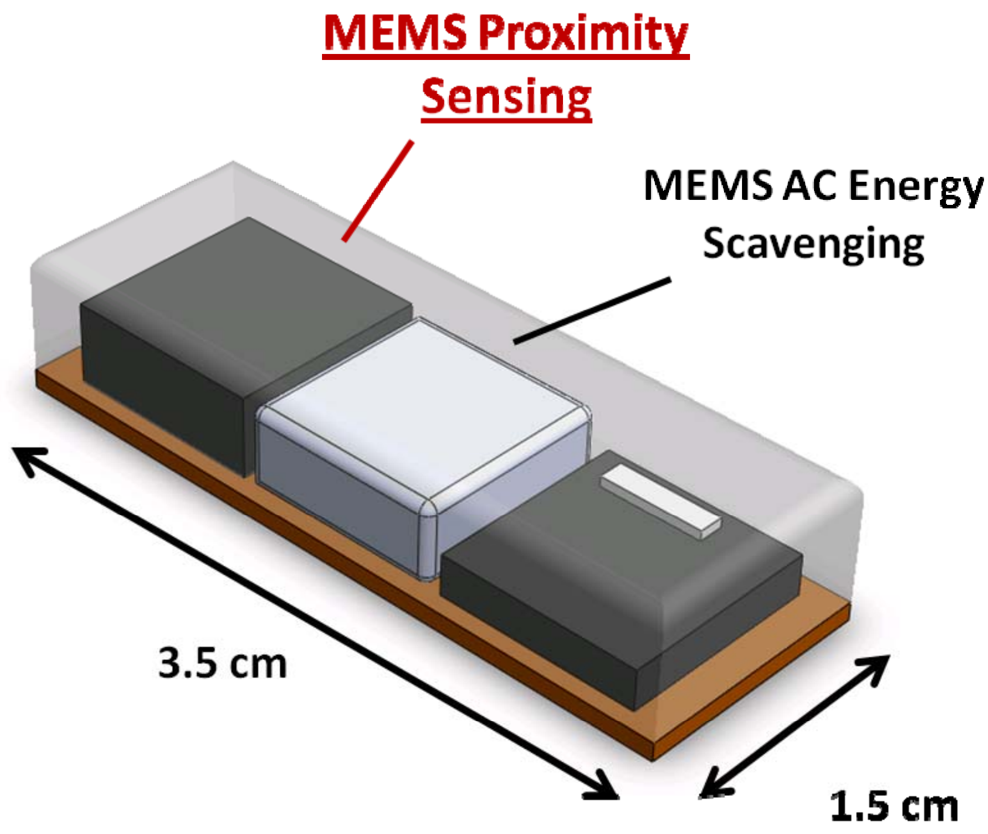
Sticky -tab Meter (Mesoscale)





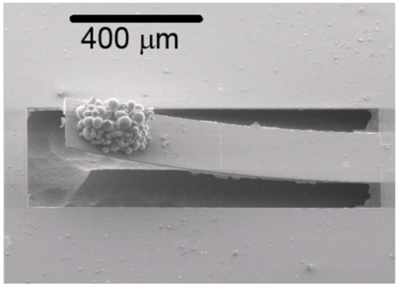
- Project to sub-meter selected circuit-breaker panels in Cory Hall, UC Berkeley
- Modules are “sticky tabs” placed on top of the circuit breaker

MEMS Proximity Sensing

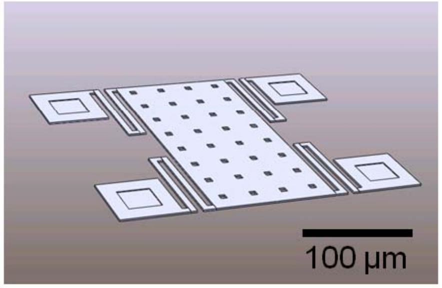


MEMS Proximity Sensing

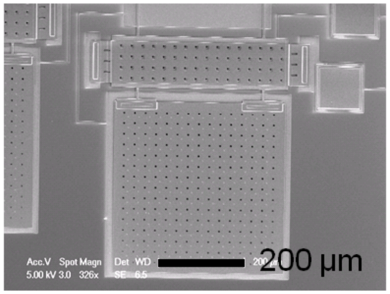
- Advantages:
  - Small and inexpensive
  - Easy to fabricate and encapsulate
  - No galvanic contacts necessary – non-invasive
  - Low or no power



Current



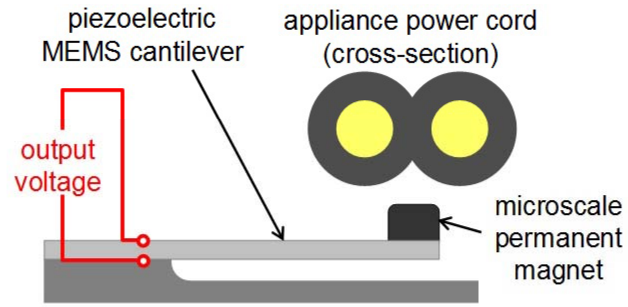
Voltage

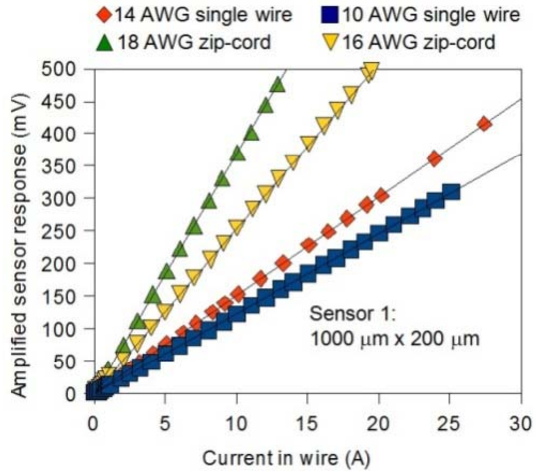


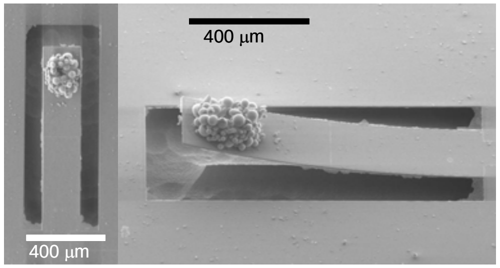
Power

MEMS AC Current Sensors

- Linearly couple to the magnetic fields around AC-carrying wires, yielding a proportional voltage.
- Microscale permanent magnets deposited onto piezoelectric cantilevers.
- Working prototypes (with amplification) have been demonstrated.



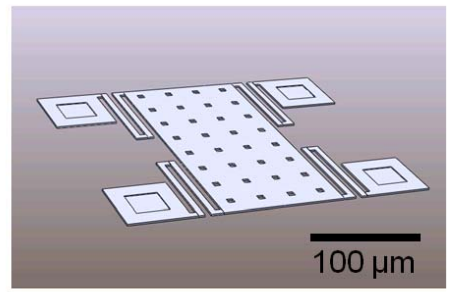




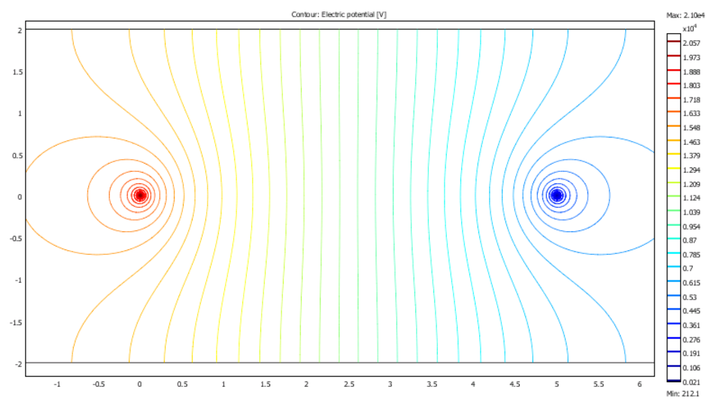
Leland et al, PowerMEMS 2006
Leland et al, PowerMEMS 2009

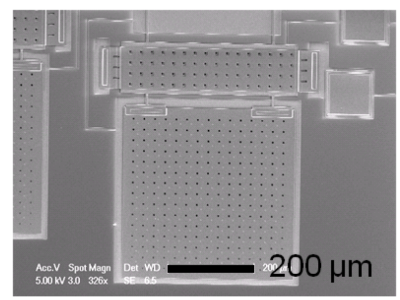
MEMS Proximity Sensors: Voltage and Power

- Capacitive electric field sensing:
  - Solid-state and MEMS
  - High-impedance MEMS transducer
  - Self-calibrating



Voltage



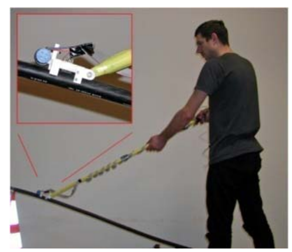


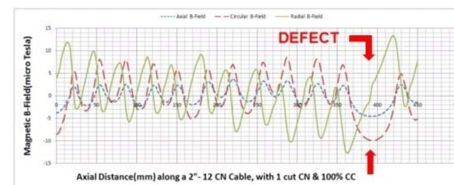
Power

Diagnostic Sensors

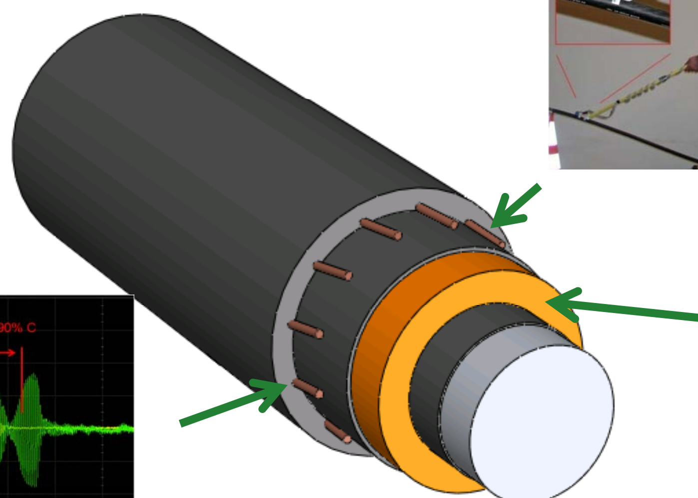
- Leverages our research on diagnostic methods for underground power distribution cables
  - On-line probing methods
  - Support *Condition-based Maintenance* of power system assets
- Will be an important part of future Smart Grid sensing

CN AMR Probing

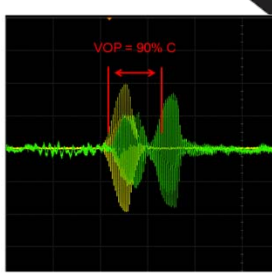




Seidel et al, ISEI 2010



RF CN Probing (Goubau)

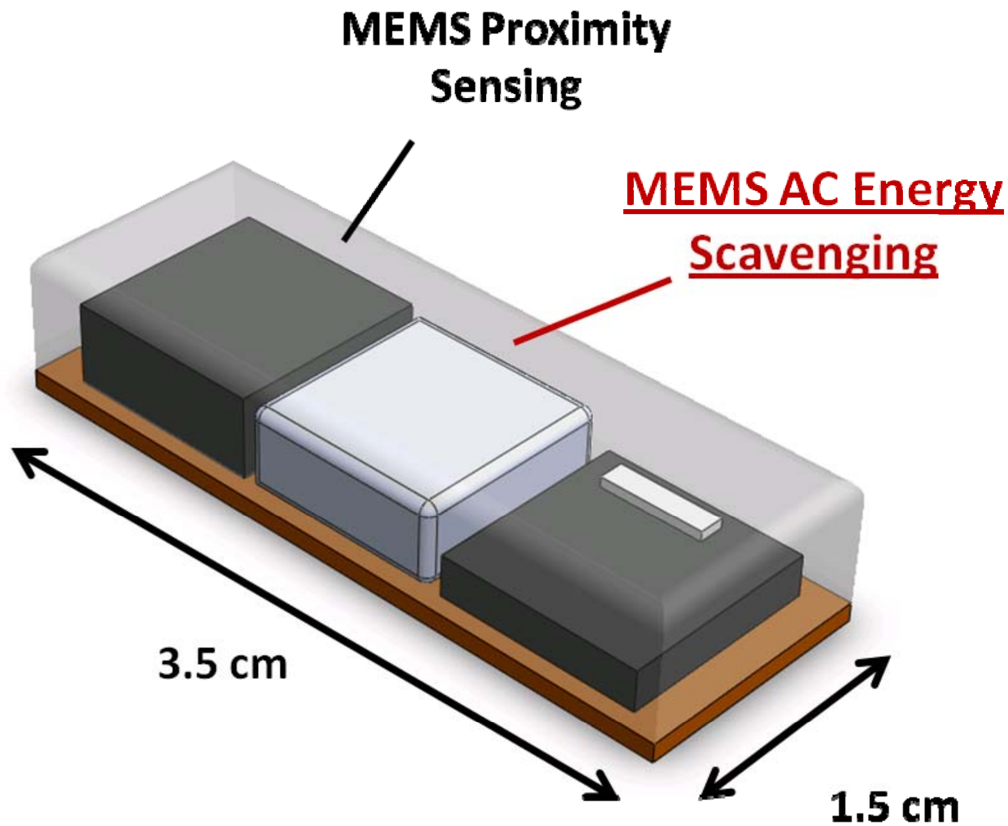


Paprotny et al, ISEI 2010

RF Dielectrometry

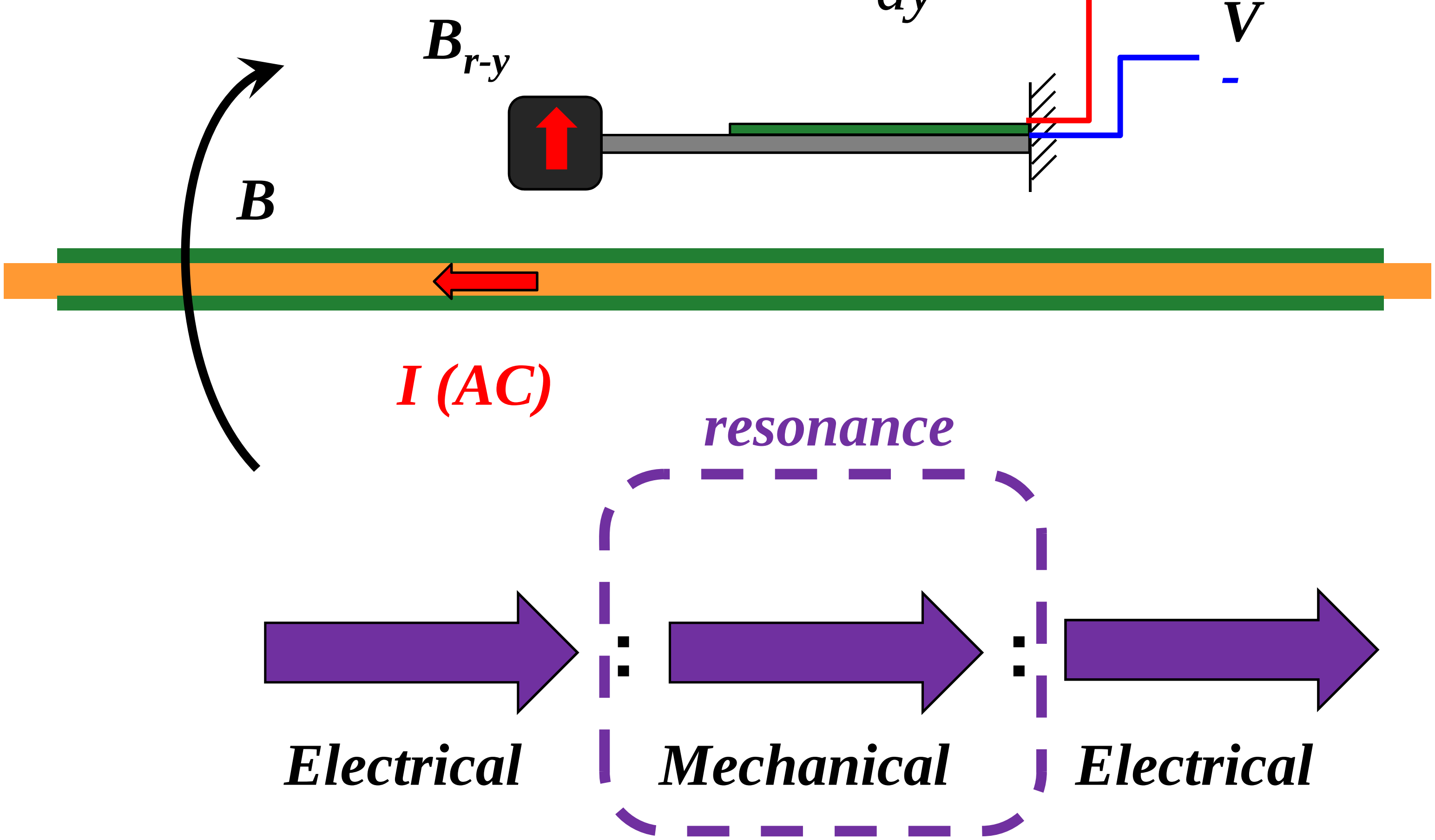
Gonzales et al, submitted to ISEI 2011

MEMS AC Energy Scavenging



Piezoelectric AC Energy Scavenger

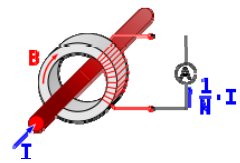
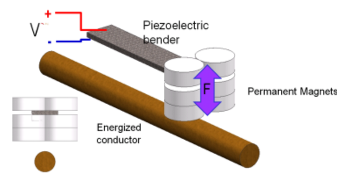
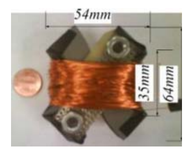
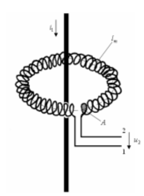
$$F = B_{r-y} \int \frac{d(H_y)}{dy} dV$$



I. Paprotny

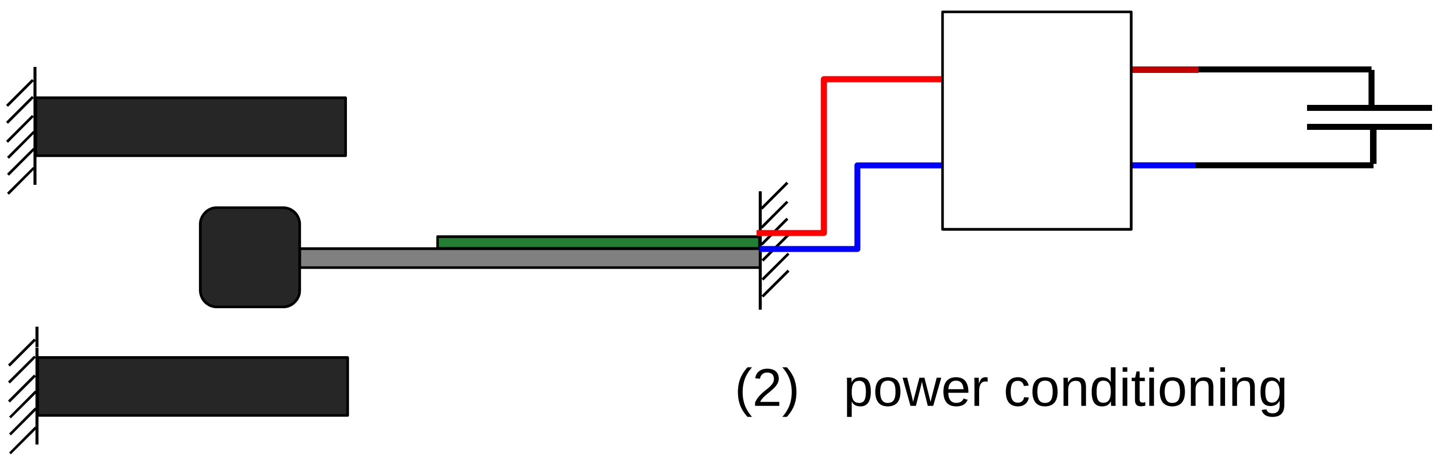
AC Energy Scavenging Overview

Power density

		+	−
Current Transformer (CT)		• Large power • No overcurrent protection	• Encircle conductor • No zip-cords
Piezoelectric AC Scavenger		• Moderate power • No encircle • Zip-cords	• Overcurrent protection • Moving parts
Coil w. flux concentrators		• No encircle • No overcurrent protection.	• Low voltage
Rogowski Coil		• No overcurrent protection.	• Low power

Images from Wikipedia, Moghe et al. ECCE 2010

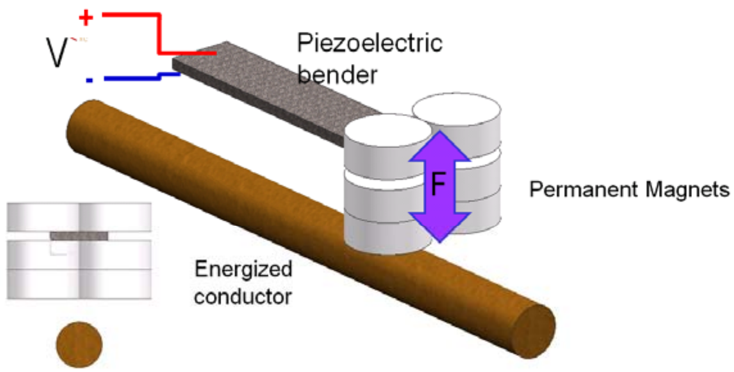
Piezoelectric AC Energy Scavenger

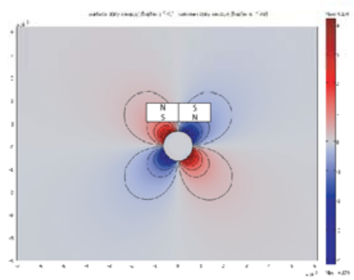


System Components

Piezoelectric AC Energy Scavenging

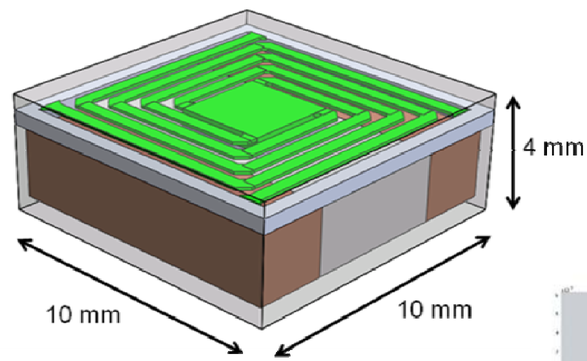
Mesoscale

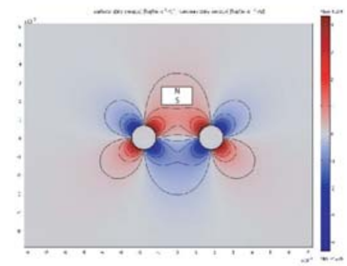




- PZT bimorph cantilever
- NdFeB magnets
- Couples to a single conductor

MEMS

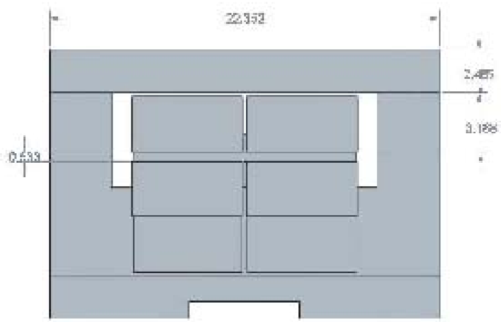


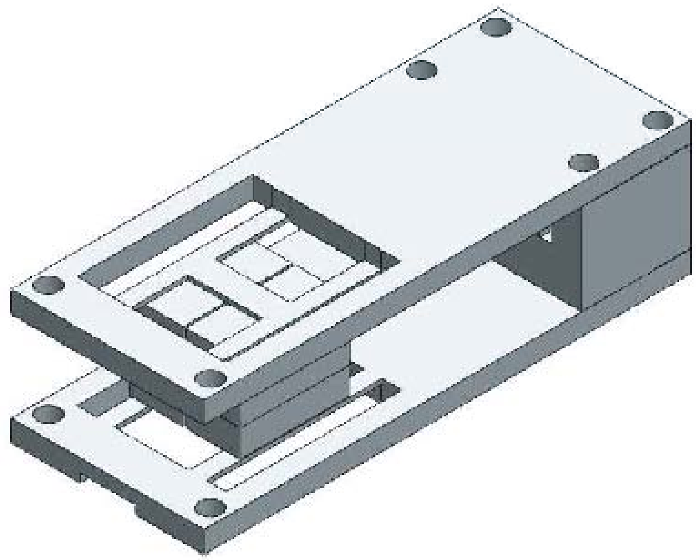


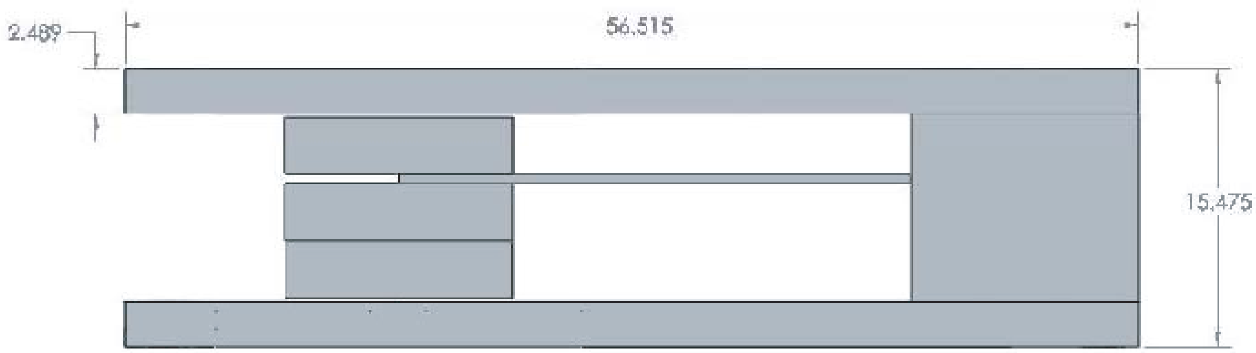
- AlN due to MEMS compatibility
- Meandering spring for resonance at power frequency
- At present, designed to couple to a zip-cord

Paprotny et al, PowerMEMS 2010

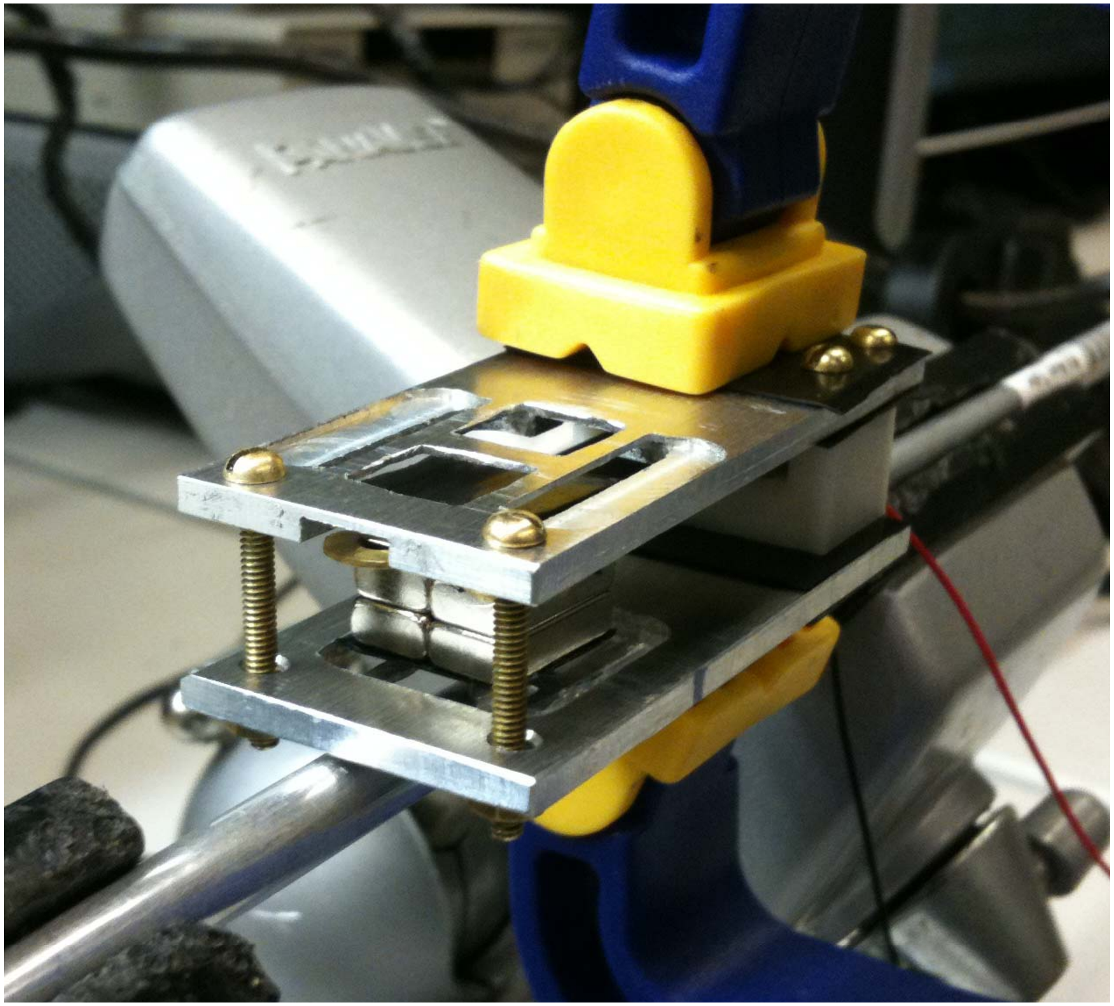
CAD Designs
(Mesoscale)





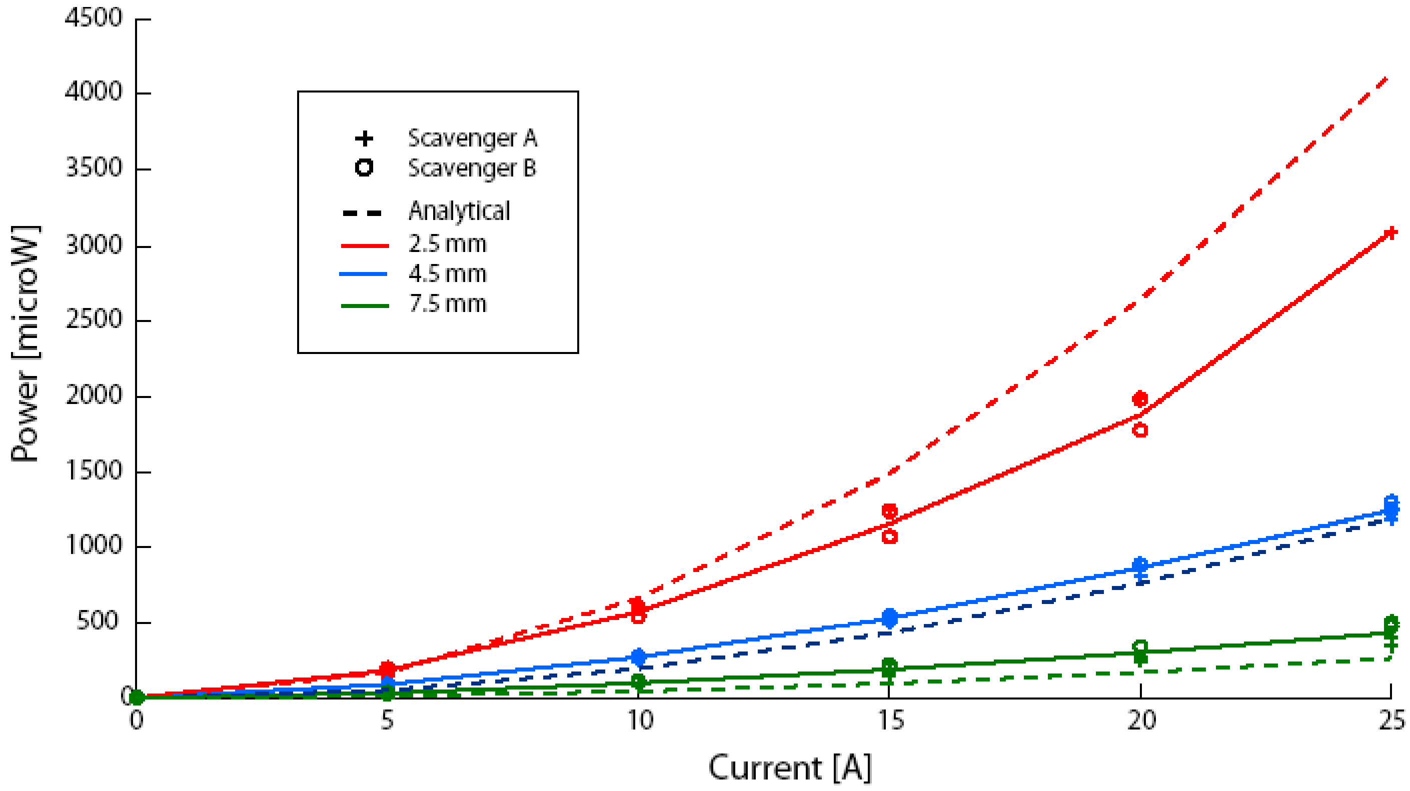


Experimental Setup
(Mesoscale)



Experimental Results

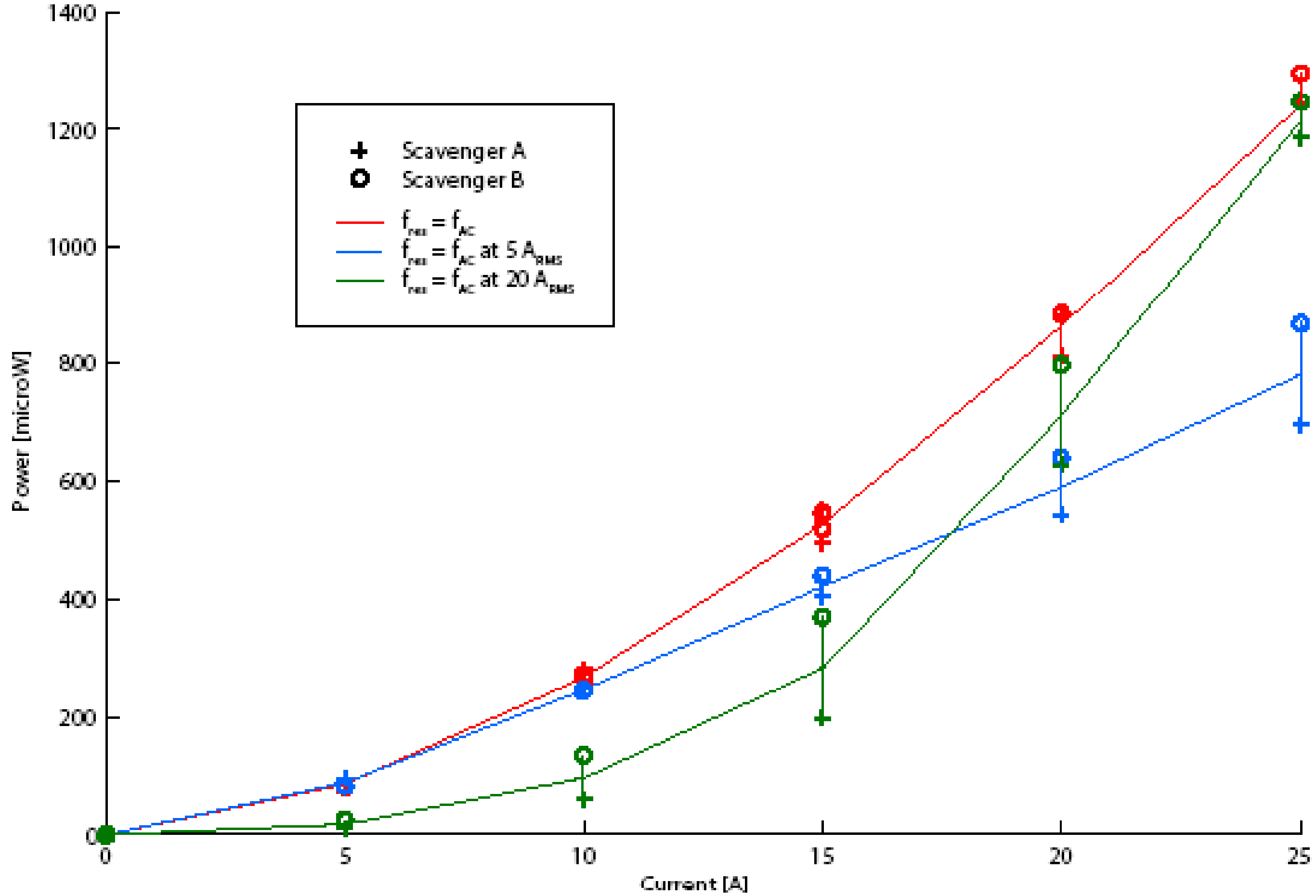
Scavenged Power



Paprotny et al, IEEE Trans. Pow. Dist. (in review)

Experimental Results

Nonlinearity



Paprotny et al, IEEE Trans. Pow. Dist. (in review)

Experimental Results
Frequency Shift

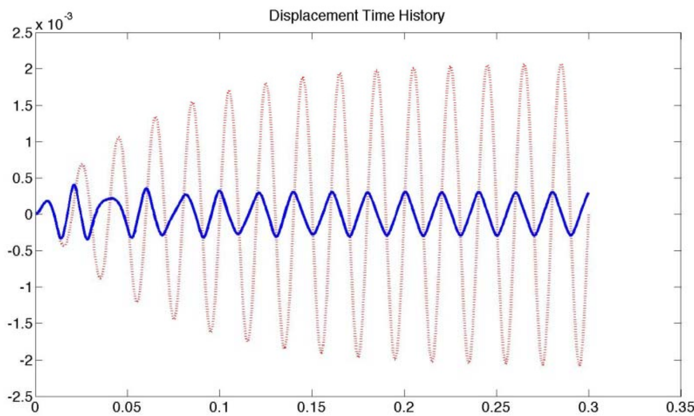
A SUMMARY OF THE RESONANT FREQUENCY SHIFT (f_r), AND THE CORRESPONDING RELATIVE POWER DROP Δ P. % FOR CURRENT SWEEP AT A DISTANCE OF 4.5 MM.

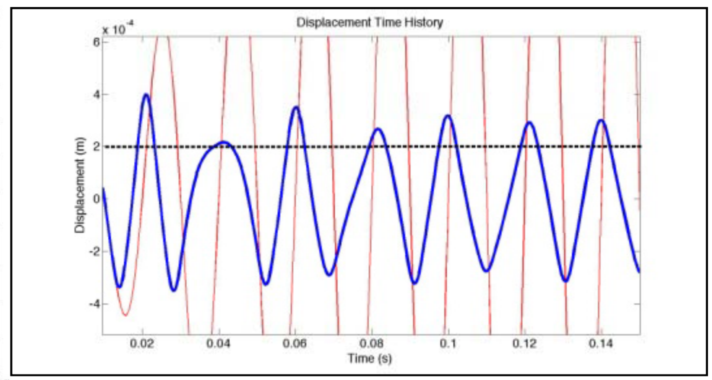
	f_r 5 A	f_r 25 A	Δf_r	Δ P.	Δ P. %
upscan					
Scavenger A	59.2 Hz	55.5 Hz	- 3.7 Hz	550 μW	44.1 %
Scavenger B	60.8 Hz	58.3 Hz	- 2.5 Hz	428 μW	33.1 %
downscan					
Scavenger A	64.3 Hz	59.8 Hz	4.5 Hz	73 μW	86.9 %
Scavenger B	62.8 Hz	59.9 Hz	3 Hz	57.7 μW	70.4 %

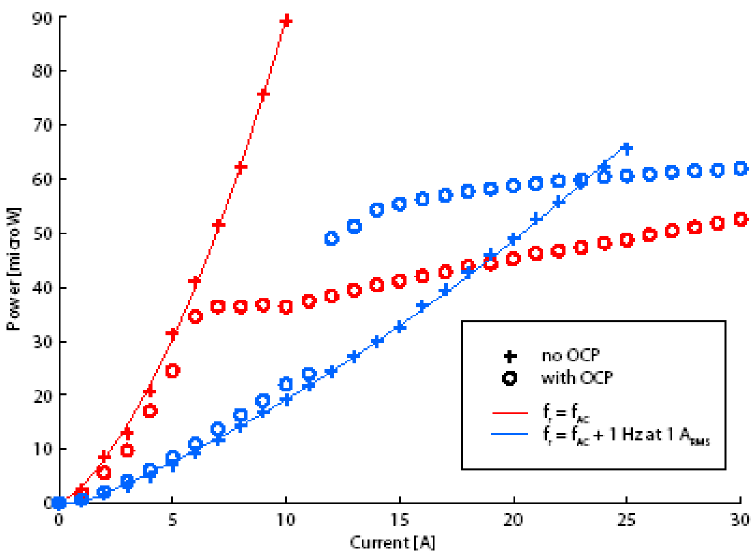
Paprotny et al, IEEE Trans. Pow. Dist. (in review)

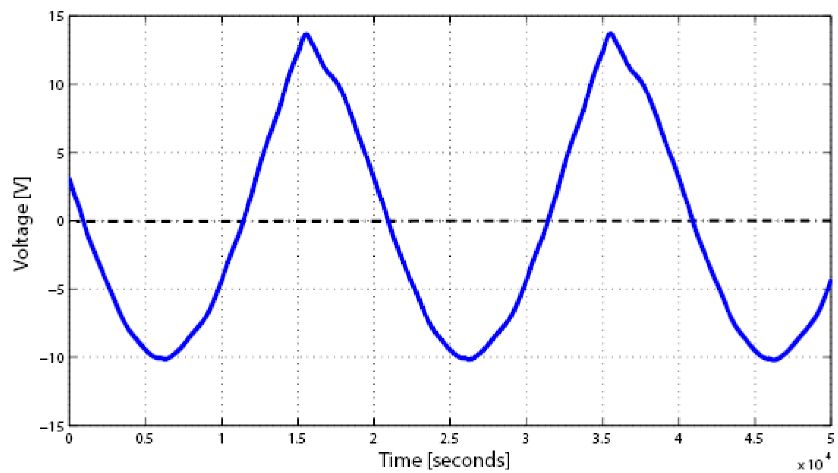
Experimental Results

Over-current Protection



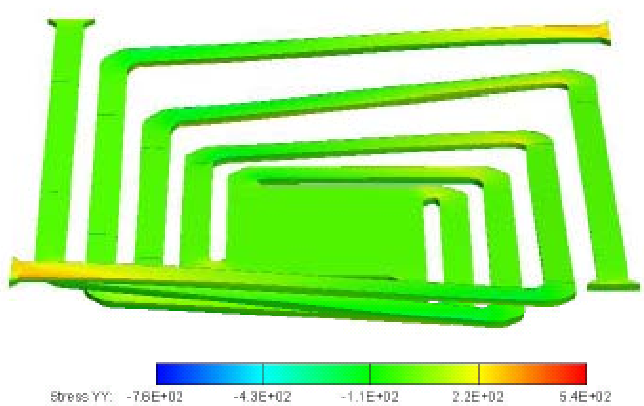




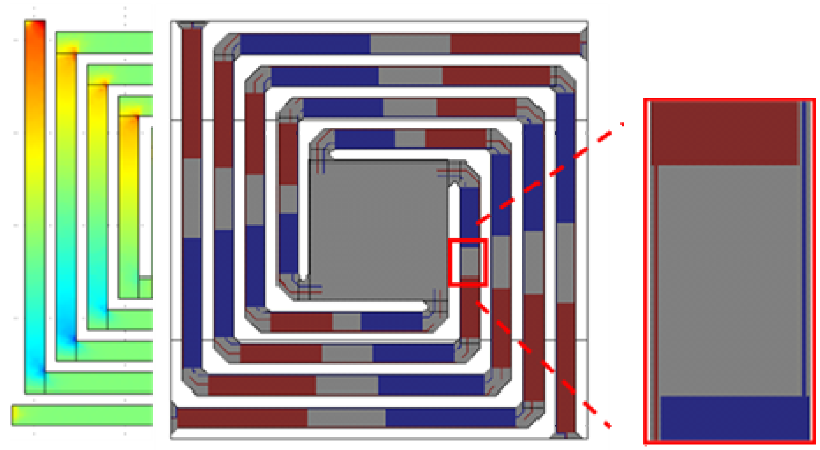


Paprotny et al, IEEE Trans. Pow. Dist. (in review)

MEMS Design



stress



electrode layout

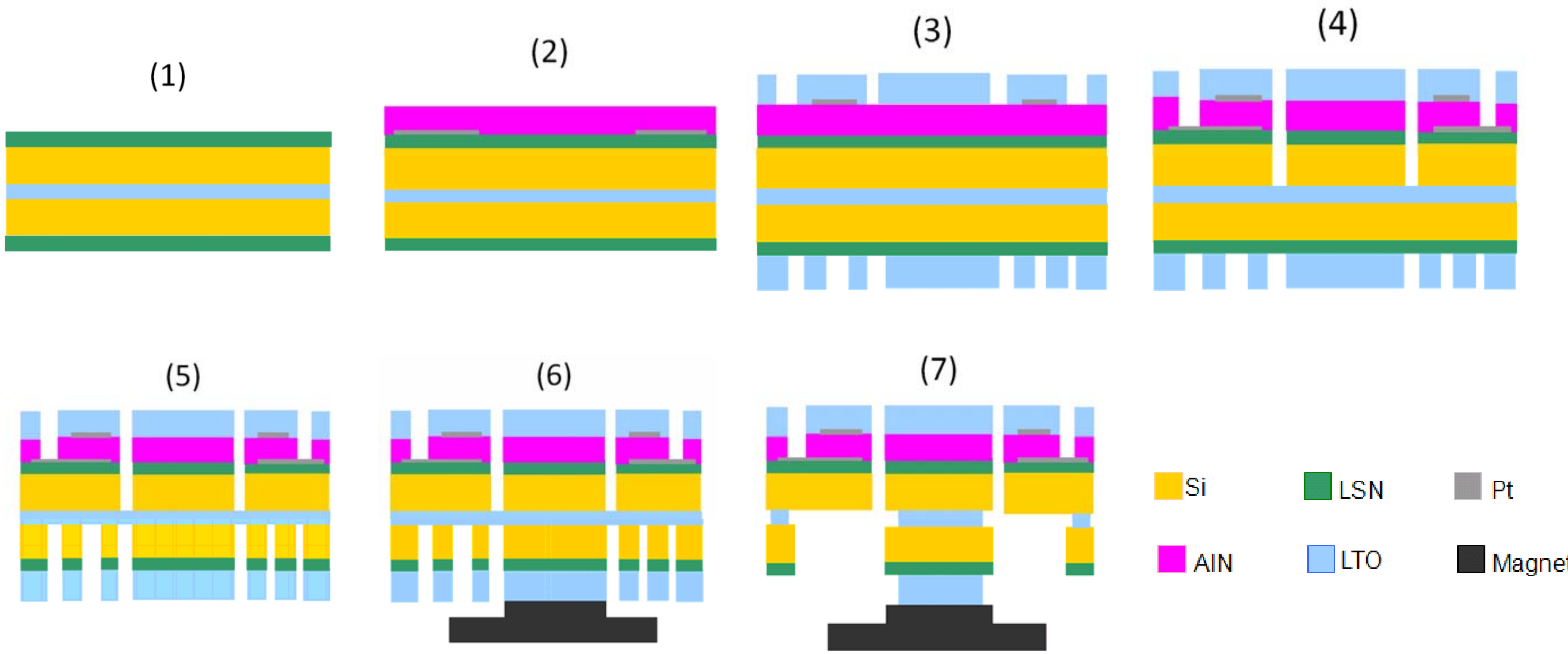
- Mechanical Design
  - Quad. fixed-fixed spring system*
  - Electrode patterned to avoid charge cancelation

- Electromechnical Modeling:
  - With single AlN layer, 2 µW
  - Multiple layers/design modifications → 10 µW

Paprotny et al, PowerMEMS 2010

**Inspired among others by A.C. Waterbury et al., IMECE 2008*

MEMS Fabrication Process



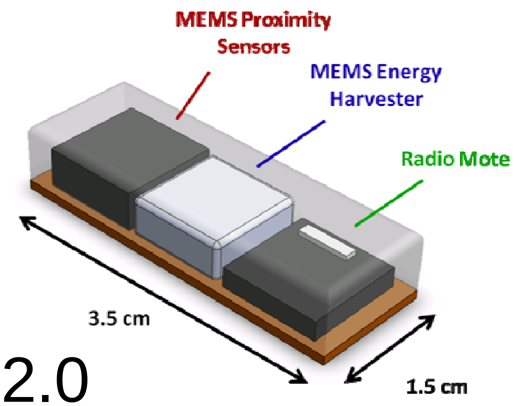
- SOI process
  - Using conventional NdFeB magnets (K&J Magnetics, Inc.)
- Fabrication ongoing !

Paprotny et al, PowerMEMS 2010

Conclusion

- Smart Grid → great opportunity for MEMS
  - The need to instrument a massive system
  - MEMS can reduce the cost by 1-2 orders of magnitude:
    - parallel fabrication
    - wafer-level integration
    - only use silicon when needed

- We are developing the “stick-on” wireless MEMS sensor module



V. 2.0

V. 4.0

Interesting Challenges

- **AC Scavenging - Overcurrent protection**
  - Steady-state overcurrent
  - Fault current (e.g., lightning strike)
- **AC Scavenging – How Small ?**
  - Efficient (MEMS) power conditioning
  - Theoretical limits ?
  - Store mechanical energy?
- **Benign Sensor Placement**
  - Prove that the sensor does not degrade equipment performance
- **Longevity Engineering**
  - Will my sensor/scavenger work for 40+ years ?

Questions ?

http://www.eecs.berkeley.edu/~igorpapa/

igorpapa@eecs.berkeley.edu