THE UNIVERSITY OF UTAH®

ENERGY HARVESTING APPLICATIONS
(ICT-ENERGY SUMMER SCHOOL 2016)

Shad Roundy, PhD

Department of Mechanical Engineering

University of Utah

shad.roundy@utah.edu

Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

Outline for Short Course

- Introduction and Linear Energy Harvesting
- Energy Harvesting Transducers
  - Electromagnetic
  - Piezoelectric
  - Electrostatic
- Wideband and Nonlinear Energy Harvesting
- **Applications**

Outline for This Lecture

- Industrial
- Light Switches (Smart Buildings)
- Tire Pressure Monitoring
- Wearable Electronics

Some Other Application Spaces

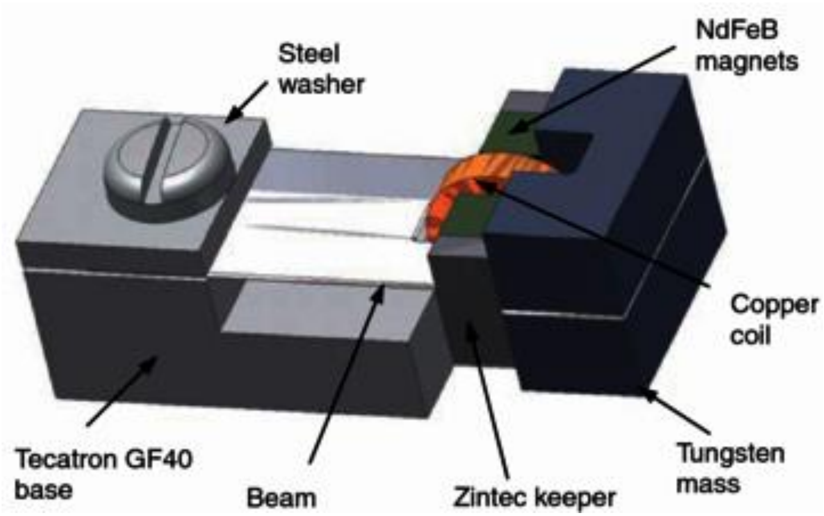
- Transportation
  - Rail cars and undercarriages
- Automotive
  - Harsh environment sensors
- Power generating pavement
  - PaveGen (www.pavegen.com)
- Asset tracking
  - Cold storage for food transport etc.
- Aerospace (sensors on/in planes and helicopters)
- Structural health monitoring sensors
  - Bridges, highways, etc.

INDUSTRIAL

Industrial Vibration Energy Harvesting

- Process control sensors in industrial environments need reliable long life power supplies
- Much of the machinery vibrates at 50 or 60 Hz
- Very low level (10’s of mG) vibrations, but very consistent and stable frequency
  - Standard linear oscillator based harvesters work well
- Industries
  - Oil and gas
  - Chemical manufacturing
  - Waste water treatment
- Vibration Energy Harvesting works well and has been in use for several years

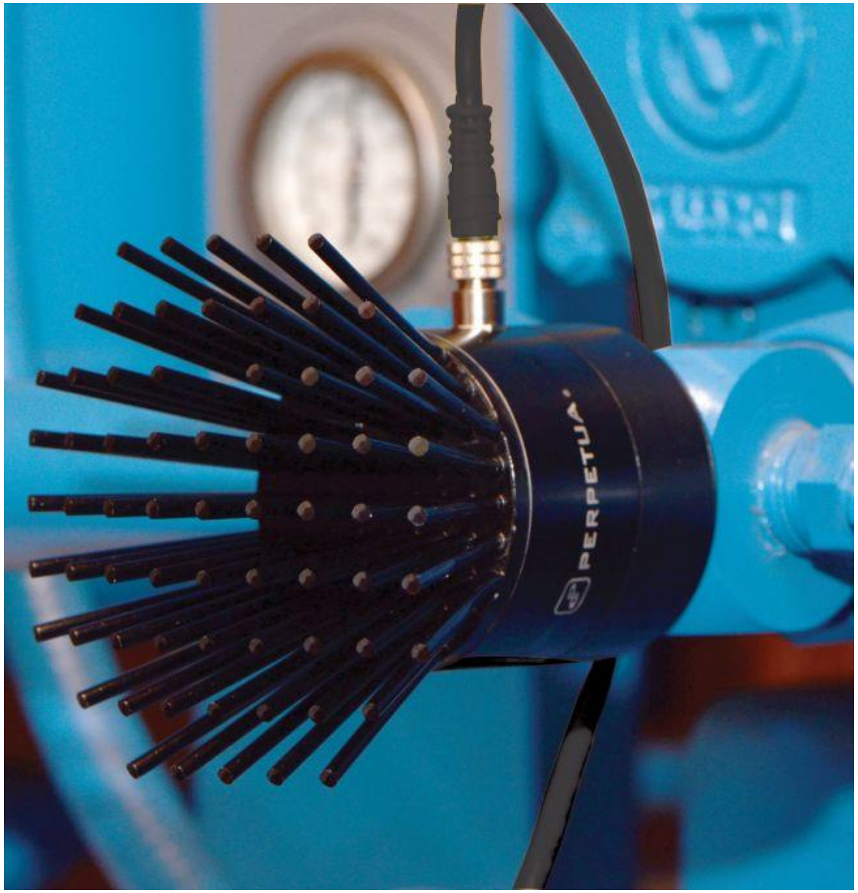
Perpetuum



http://www.perpetuum.com/

Beeby et. al, JMM, 2007

Perpetua Power (Thermoelectric)



http://www.perpetapower.com/

LIGHT SWITCHES

Why Light Switches?

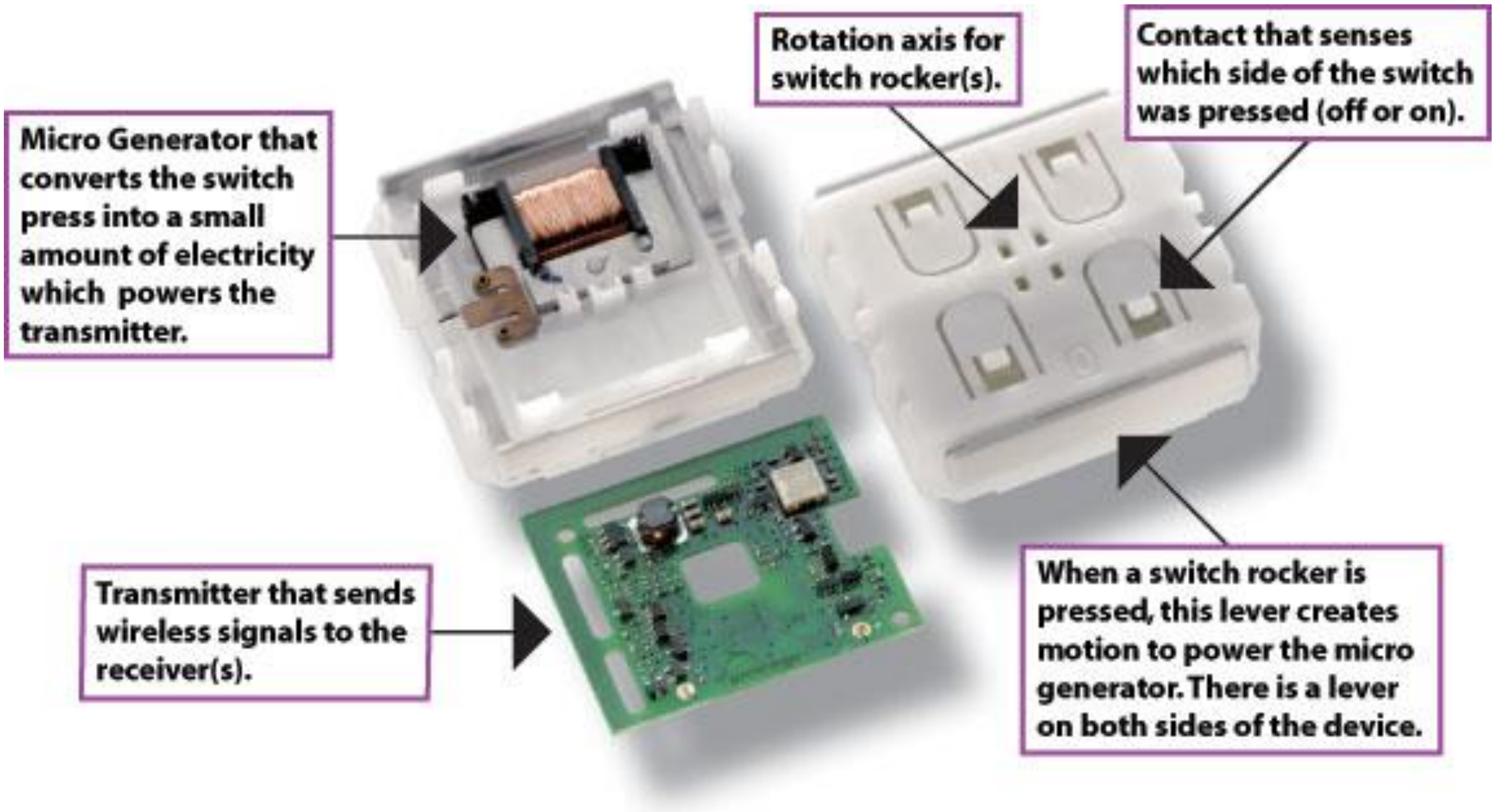
- It is expensive to wire light switches for new and retrofitted buildings
- Wireless light switches can be moved based on users' convenience without rewiring
- Changing batteries in light switches in large buildings with many many switches is a significant maintenance cost and headache
- Light switches can integrate into smart building control schemes

Enocean Light Switches

EnOcean, www.enocean.com

- Fixed amount of energy input, very roughly 4 N x 1 mm = 4 mJ max.
- Use Enocean's radio and communications protocol
- Needs somewhere around 100 uJ for a transmission, or 2.5% efficiency
- I believe efficiency is closer to 10%
- Note, early designs were piezoelectric

Enocean Light Switches



http://www.adhocelectronics.com/Products/Wireless-Lighting-Control

Rotational Switch

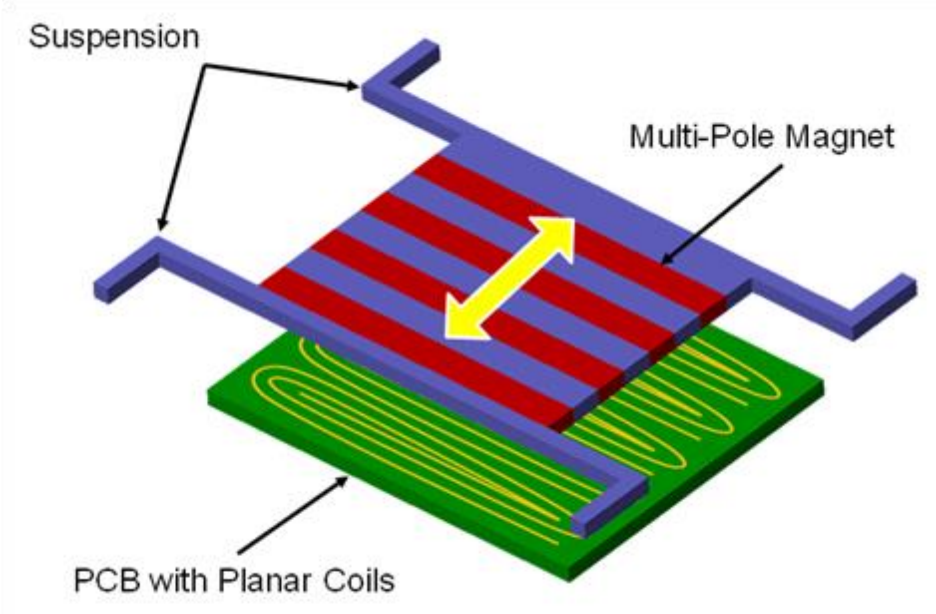
Developed for EcoHarvester. Design published in Roundy and Takahashi, Sensors and Actuators, 2013

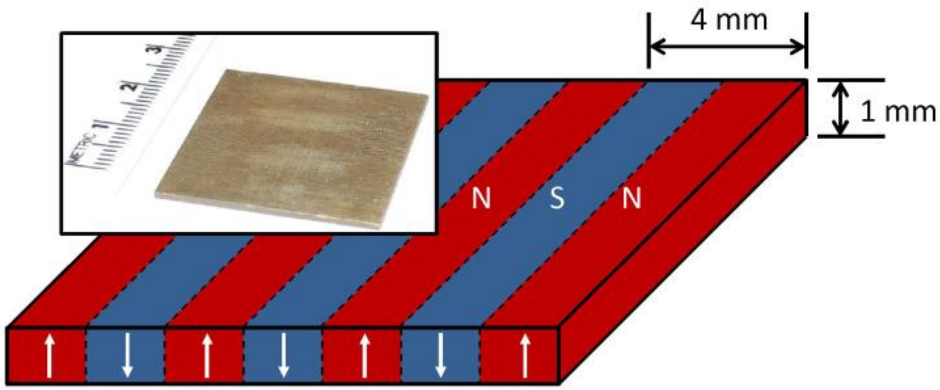
Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

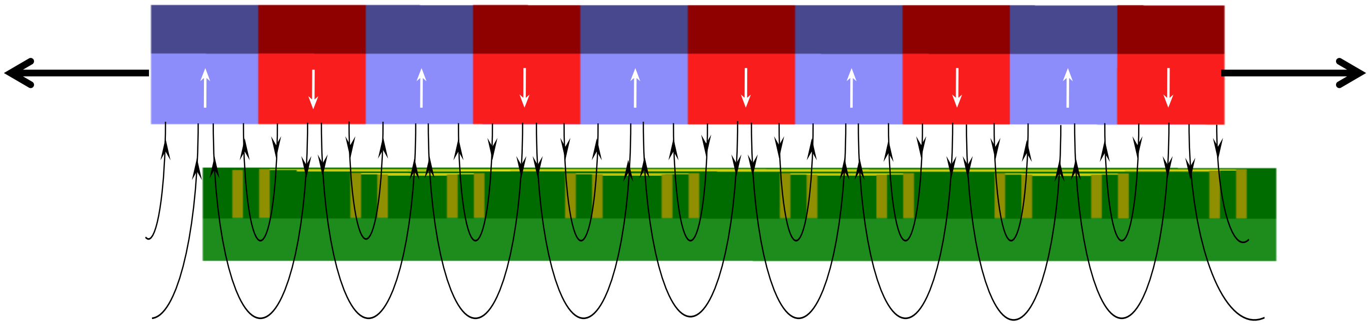
Objectives

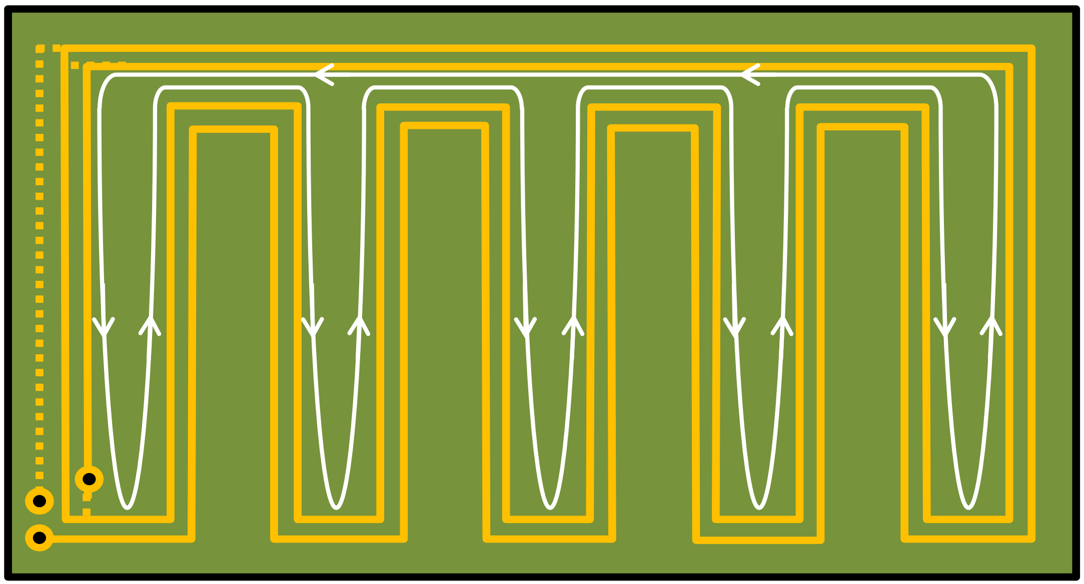
- Create (and understand) an energy harvesting transducer for a light switch that is
  - Planar and thin
  - Cheap
  - Highly efficient
  - Leverages new magnetic sheet manufacturing technology

Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH


Suspension
Multi-Pole Magnet
PCB with Planar Coils


4 mm
1 mm
N
S
N

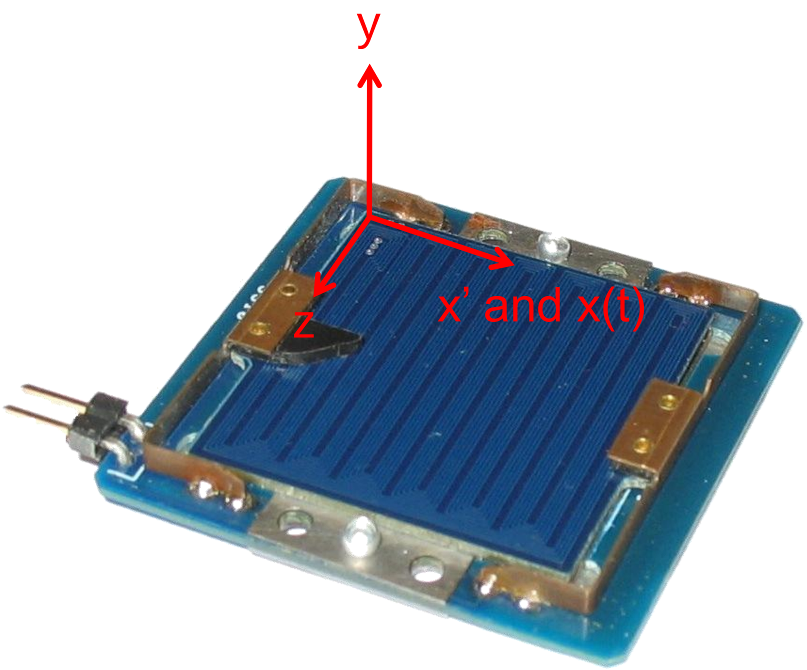


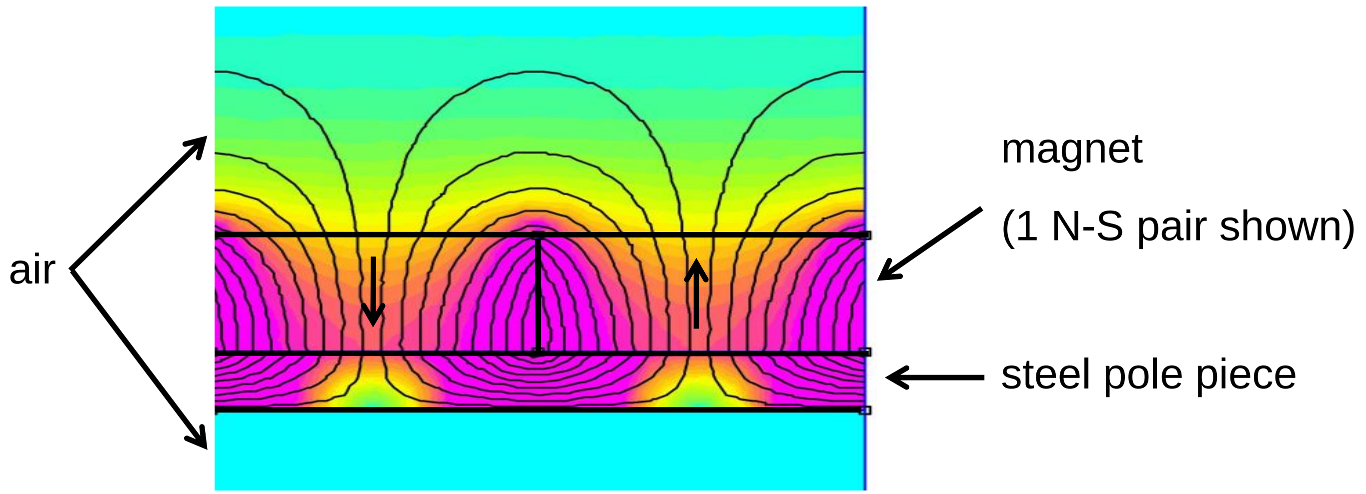


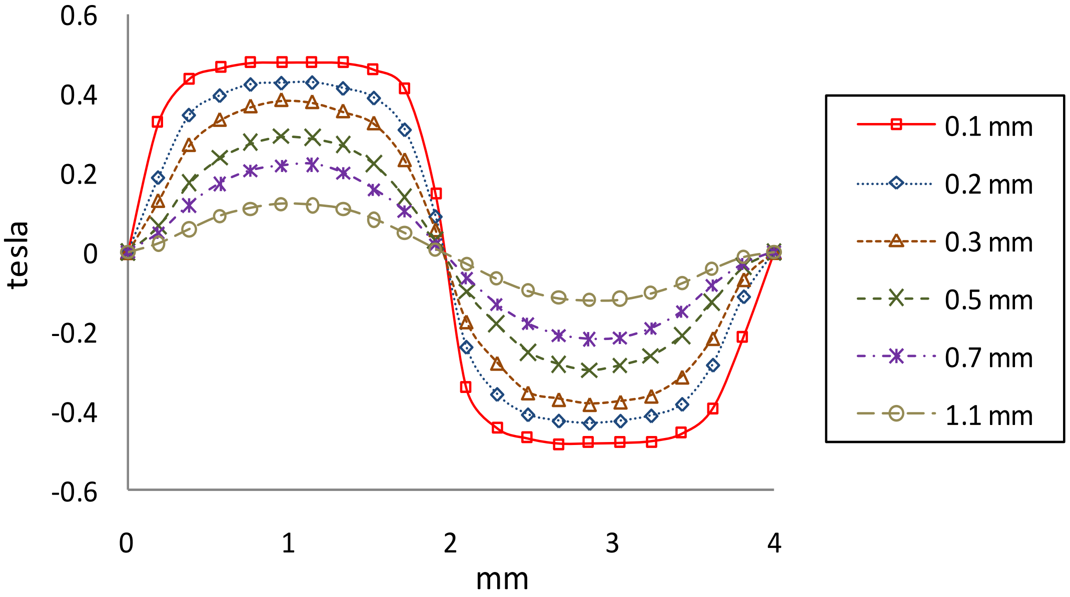
$$\frac{di}{dt} = -\frac{R+R_c}{L}i + \frac{1}{L}V_s$$

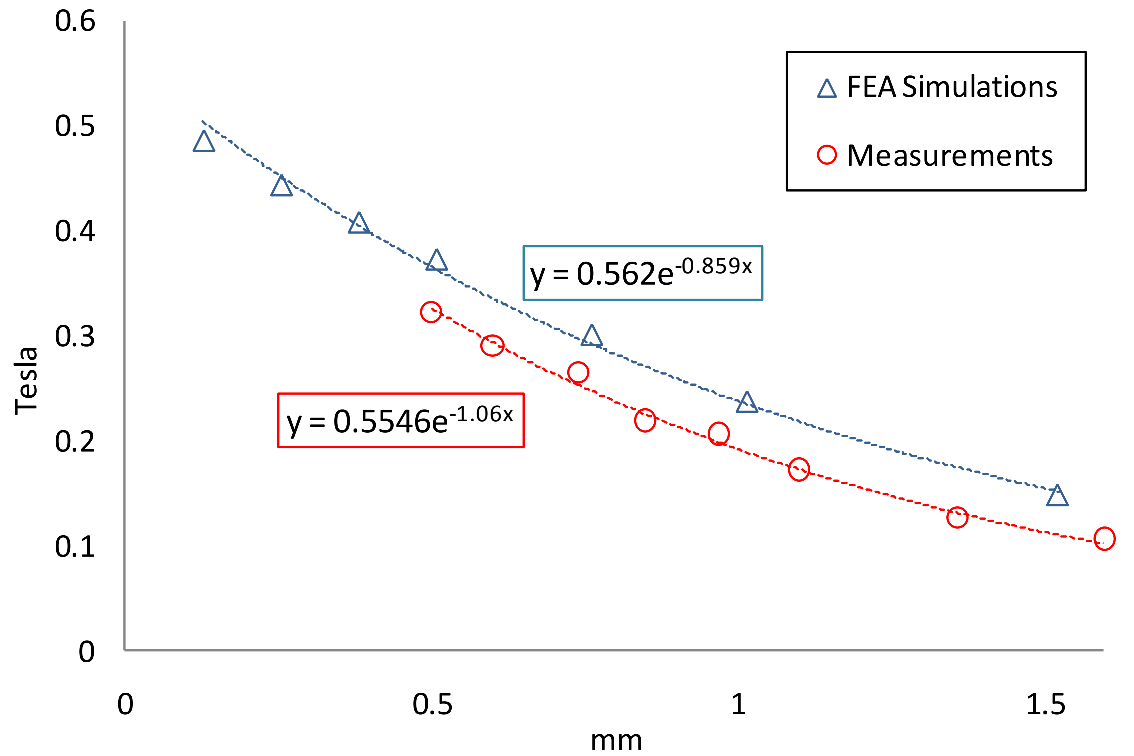
$$V_s = -\frac{d\Phi}{dt} = -Nl\frac{d}{dt}\left(\int_{x'_1}^{x'_2} B_y(x')dx'\right)$$

$$m\ddot{x} + b\dot{x} + N\left(i\vec{l} \times \vec{B}\right) + kx = F_{in}(t)$$

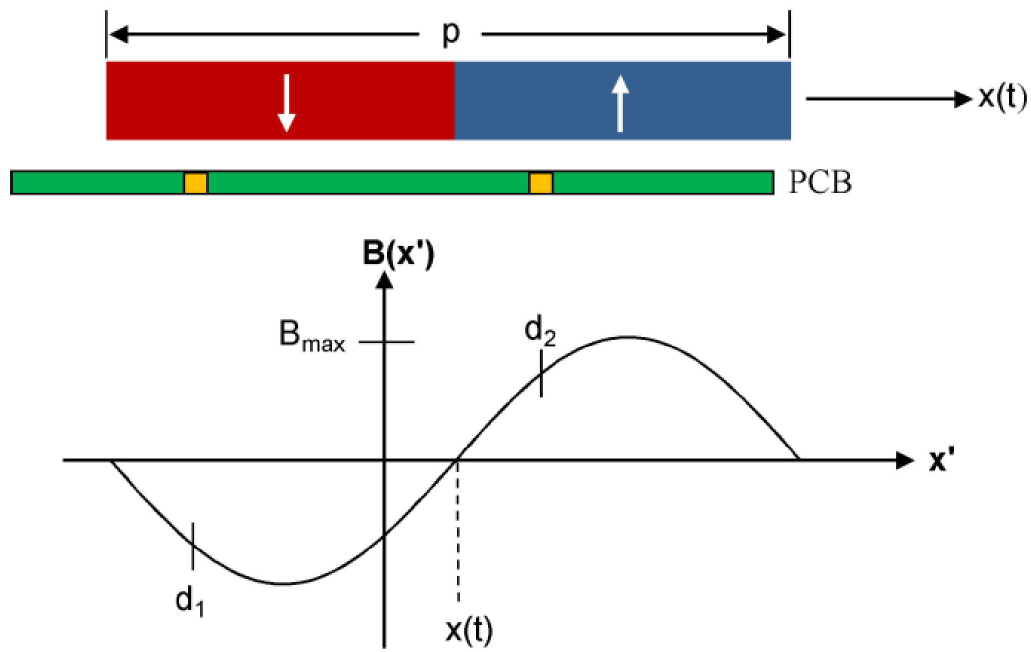



air
magnet
(1 N-S pair shown)
steel pole piece


0.6
0.4
0.2
0
-0.2
-0.4
-0.6
tesla
0
1
2
3
4
mm
0.1 mm
0.2 mm
0.3 mm
0.5 mm
0.7 mm
1.1 mm



$$B_y(x') = B_{\max} e^{-\alpha y(i)} \sin\left(\frac{2\pi}{p} (x' - x(t)) \right)$$

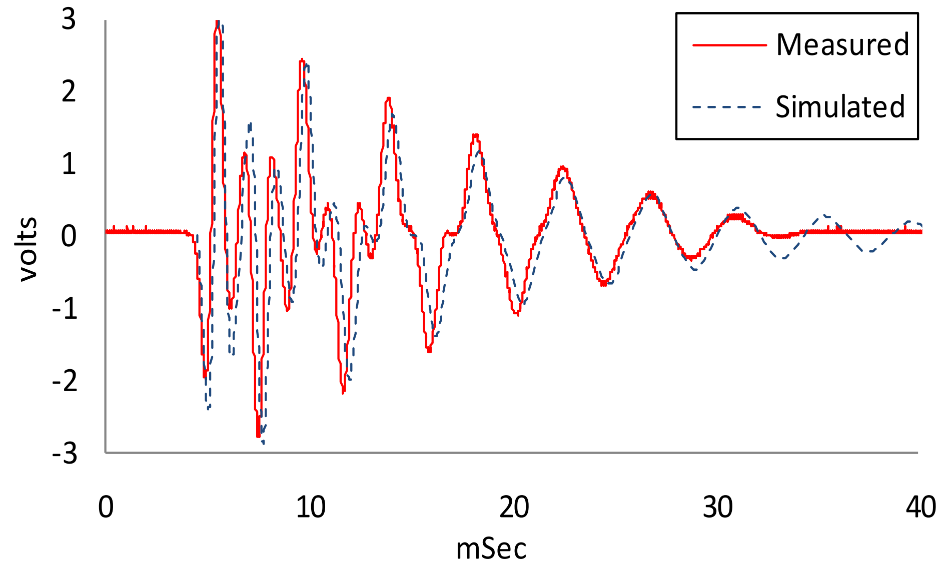


$$\frac{d\Phi}{dt} = Nl\,\frac{d}{dt}\left(\int_{x'_1}^{x'_2} B_y(x')\,dx'\right)$$

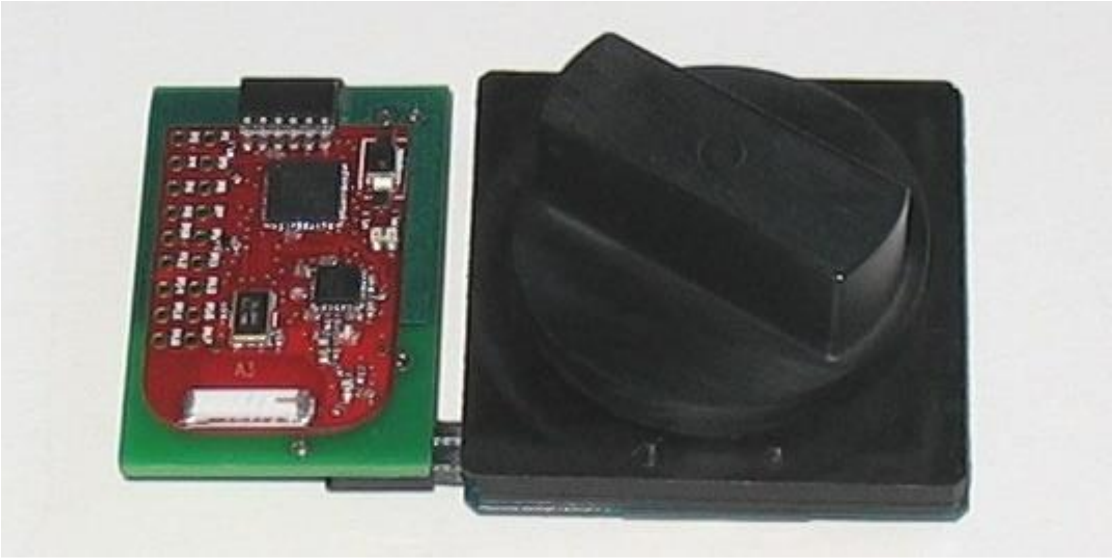
$$\frac{d\Phi}{dt} - NlB_{\max}e^{-\alpha y(i)}\dot{x}\left\{\left[\sin\left(\frac{2\pi d_2}{p}\right)-\sin\left(\frac{2\pi d_1}{p}\right)\right]\cos\left(\frac{2\pi}{p}x(t)\right)-\left[\cos\left(\frac{2\pi d_2}{p}\right)-\cos\left(\frac{2\pi d_1}{p}\right)\right]\sin\left(\frac{2\pi}{p}x(t)\right)\right\}$$

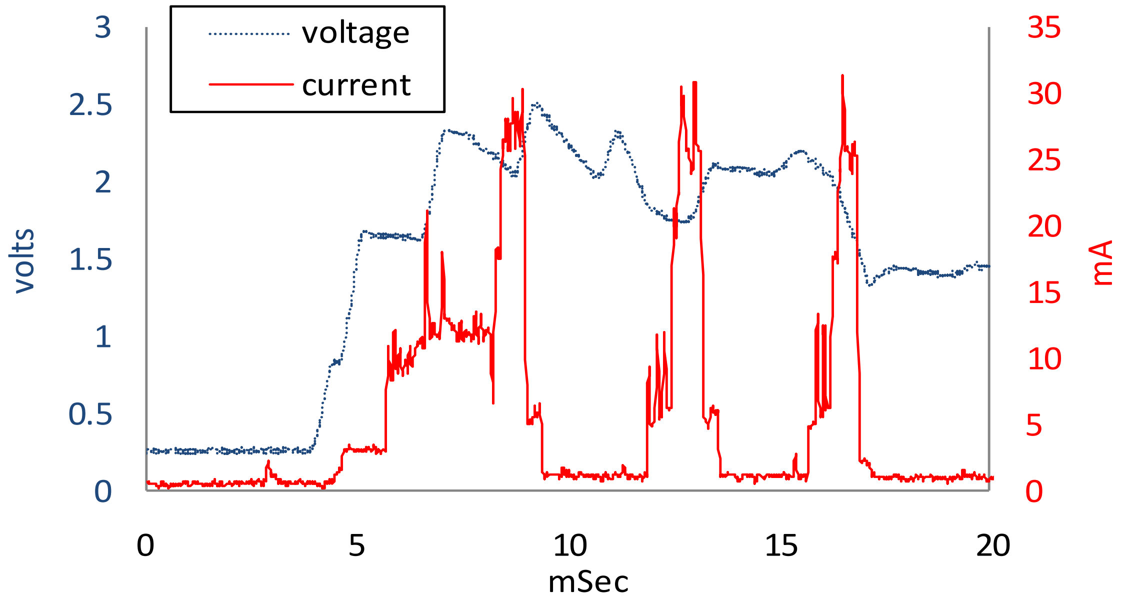
d_1, d_2 refer to lateral position of conductors for a given coil.

$y(i)$ refers to the distance from the magnet surface of the i^th layer



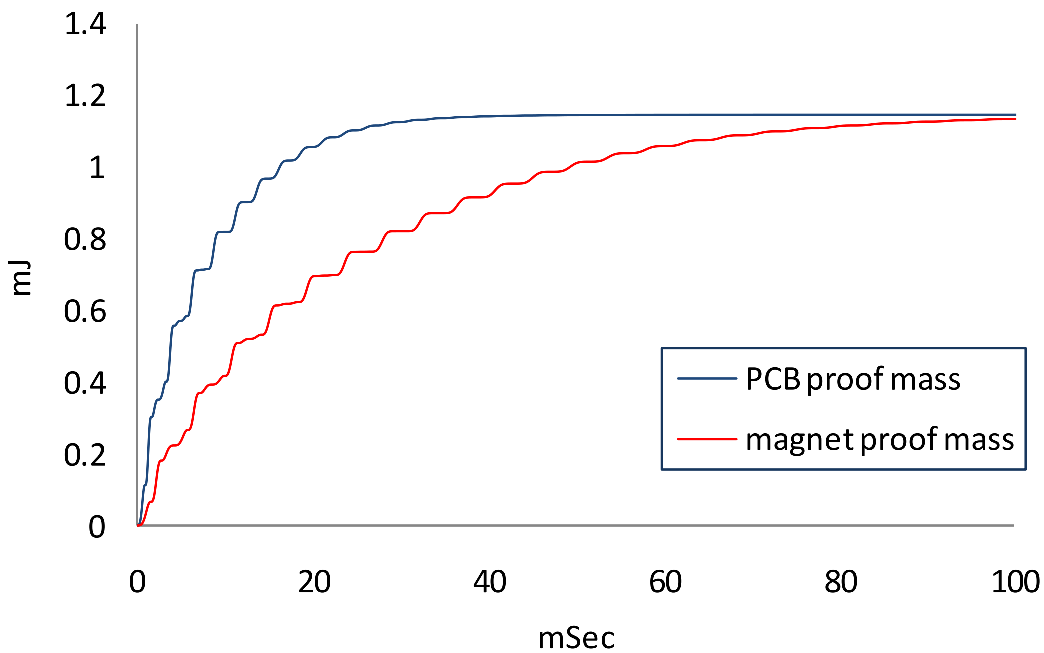
- Input displacement of 2mm (12 N max force, 12 mJ input)
- 1.1 mJ output per actuation
- 9% efficiency





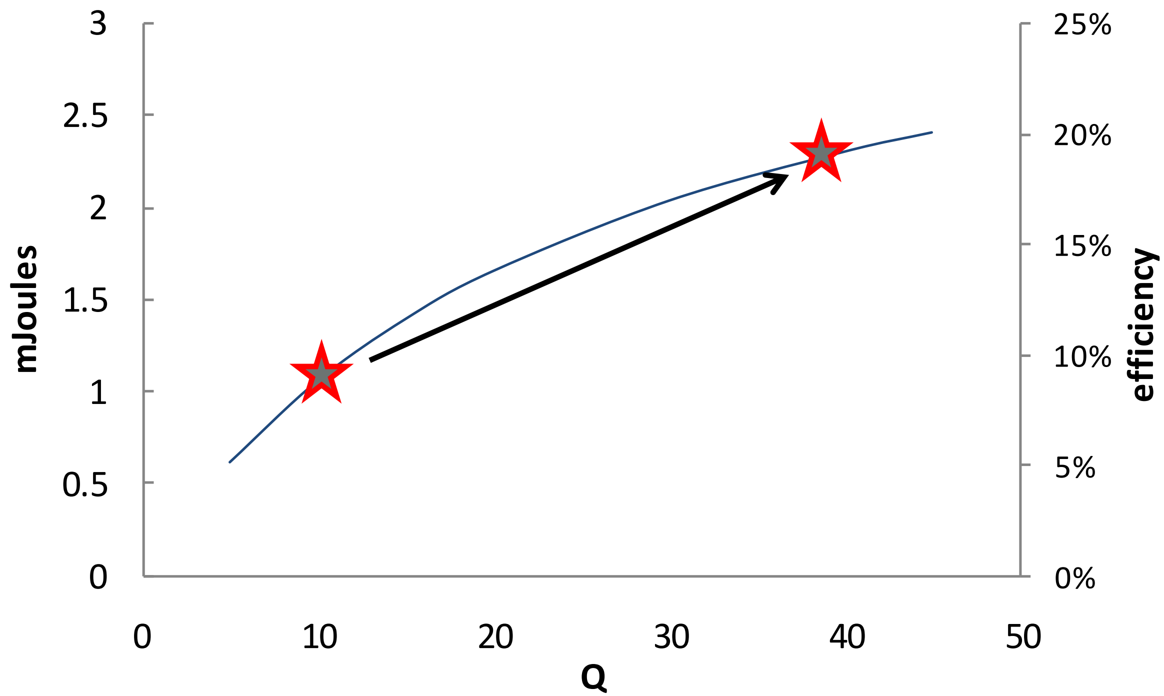
voltage
current
volts
mA
mSec
3
2.5
2
1.5
1
0.5
0
35
30
25
20
15
10
5
0
0
5
10
15
20

Magnet Vs. PCB as Proof Mass



- Total energy generated is the same
- Lighter proof mass generates energy faster with higher initial voltages
- Heavier proof mass rings down slower, generates for a longer time

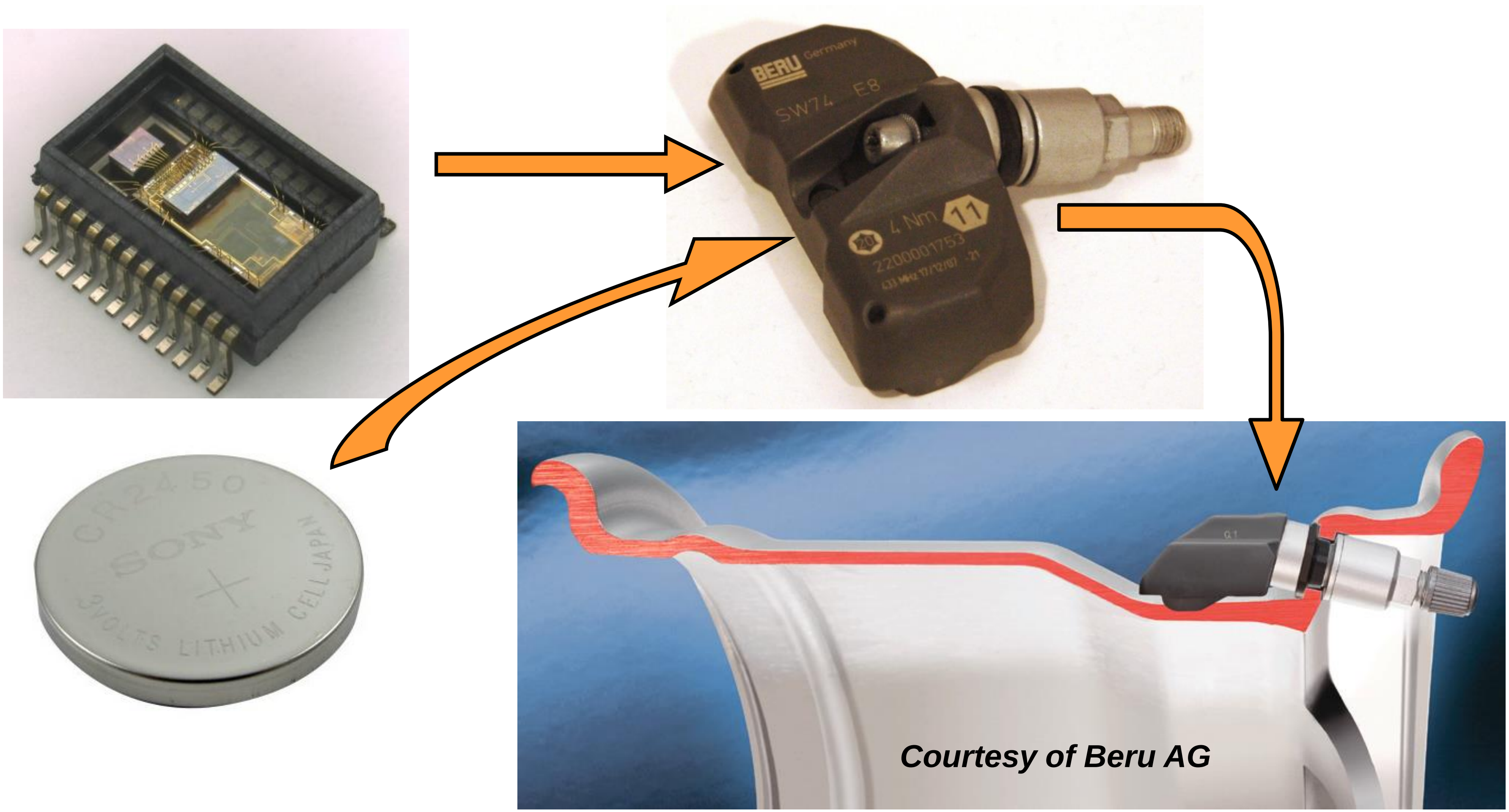
Energy vs. Mechanical Q



- We're operating at a total Q of just over 10.
- Effective Q from electromagnetic coupling is 65.
- Improved mechanical design could roughly double energy output.

TIRE PRESSURE MONITORING SYSTEMS

Tire Pressure Sensing Module



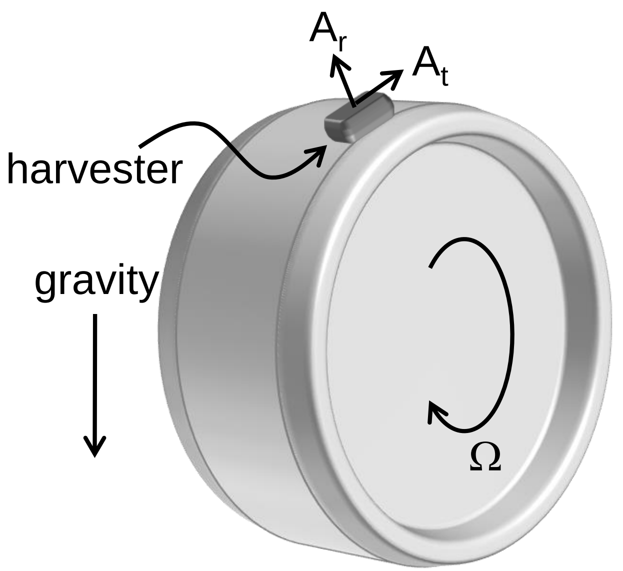
Courtesy of Beru AG

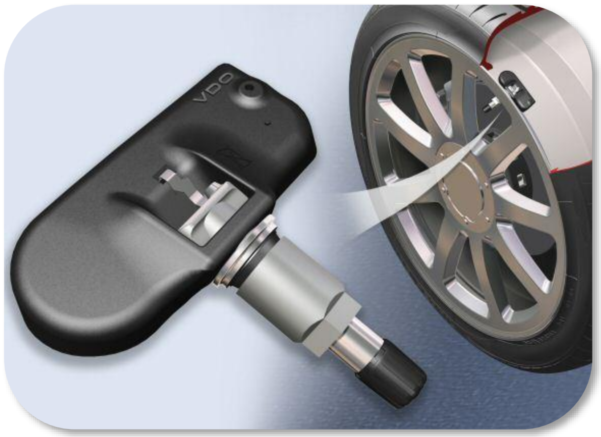
Roundy, PowerMEMS, 2008

What's Wrong With A Battery?

- Concerns With Batteries
  - Limited Lifetime
    - Life Requirement Is 10 Years
    - Will Batteries Last?
  - Concerns At Temperature Extremes
    - High Internal Resistance At -40 C
    - Reliability At +125 C
  - Expensive
    - Cost ~ $0.50
  - Polluting
    - But This Isn't A Really Big Application In The Battery World

The Energy Harvesting Problem

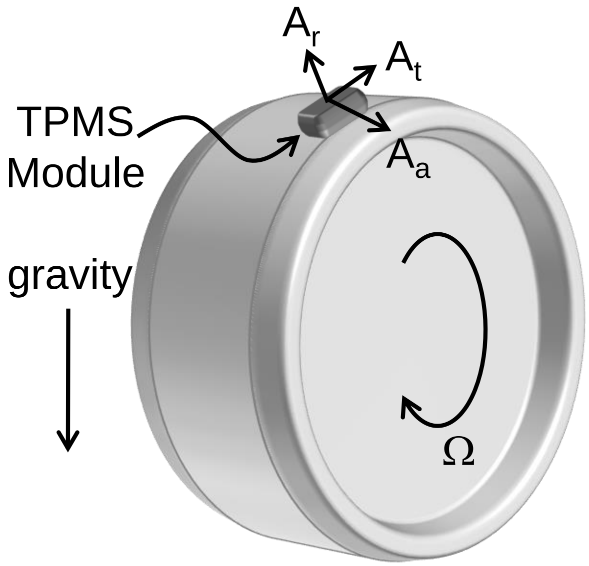


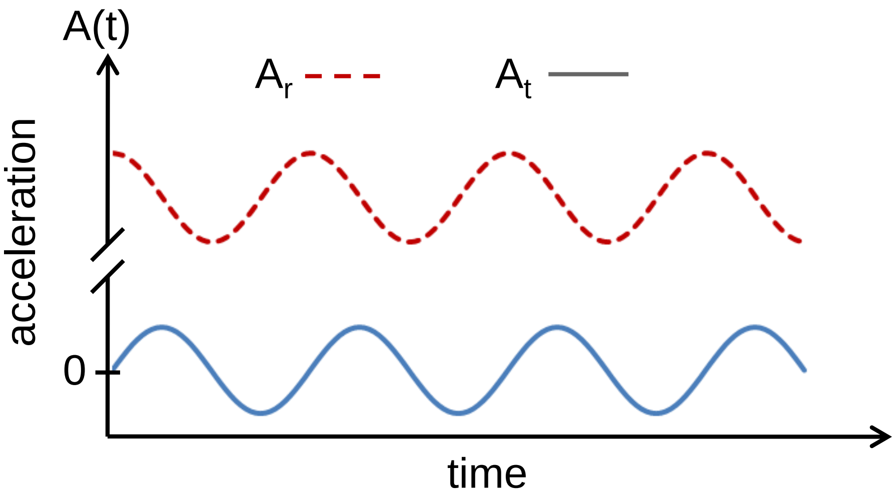


- Three critical requirements drove our solution
  - First transmission within first 100 tire revolutions, no rechargeable battery
  - During regular driving must transmit at least once per minute – corresponds to at least 20 uW power generation
  - Low profile

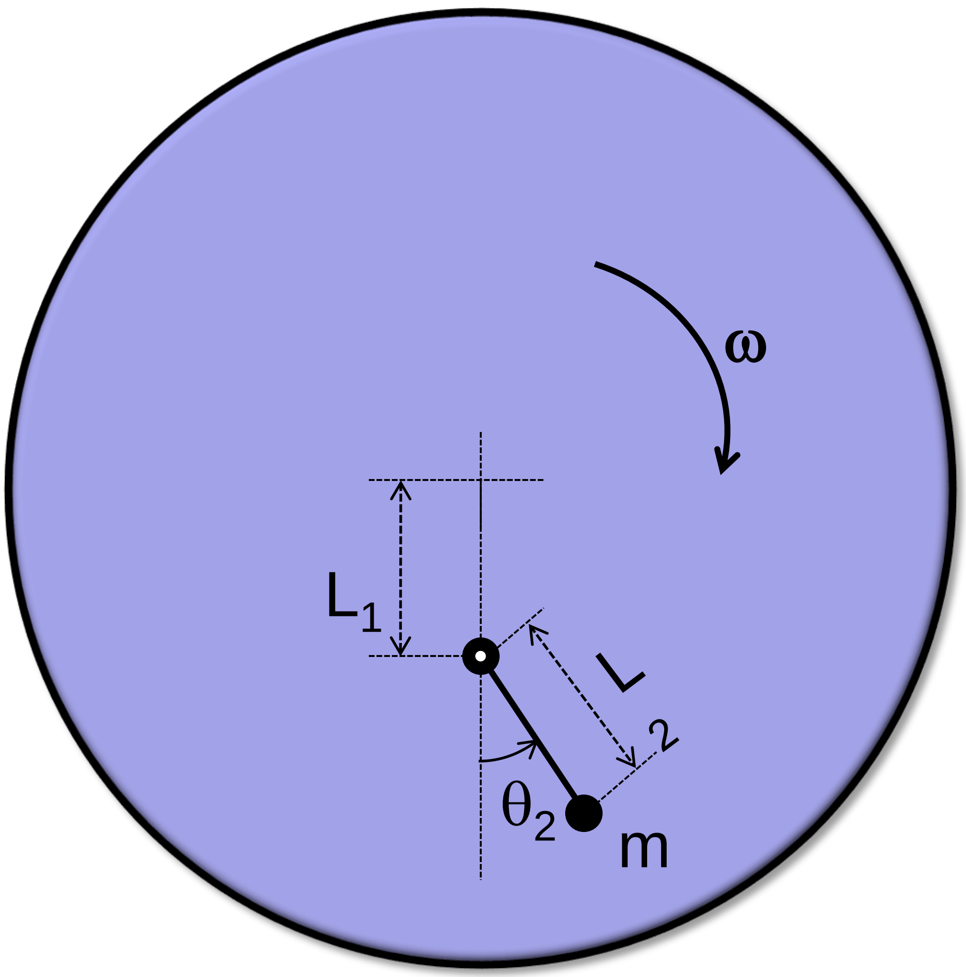
Roundy et. al., Transducers 2013

Acceleration Signals





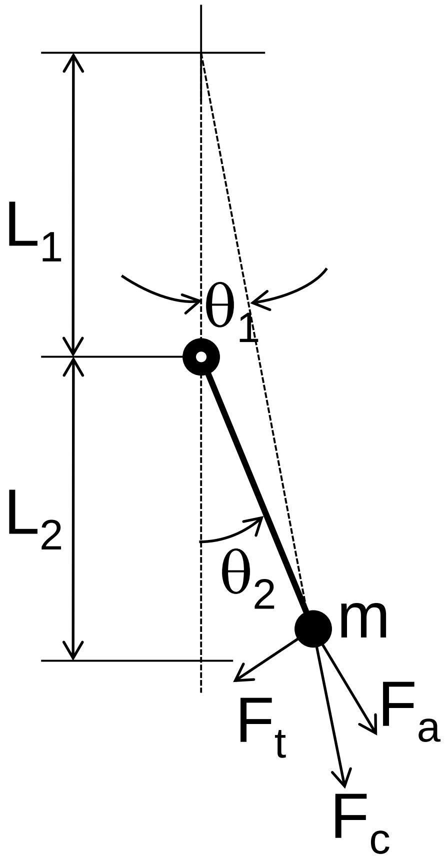
Self-tuning Pendulum System



- Pendulum located on rotating wheel or disc offset from center
- Centripetal acceleration will tend to straighten pendulum
- Restoring torque on mass (m) is a function of angular displacement (θ_2)
- Looks like a spring

Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

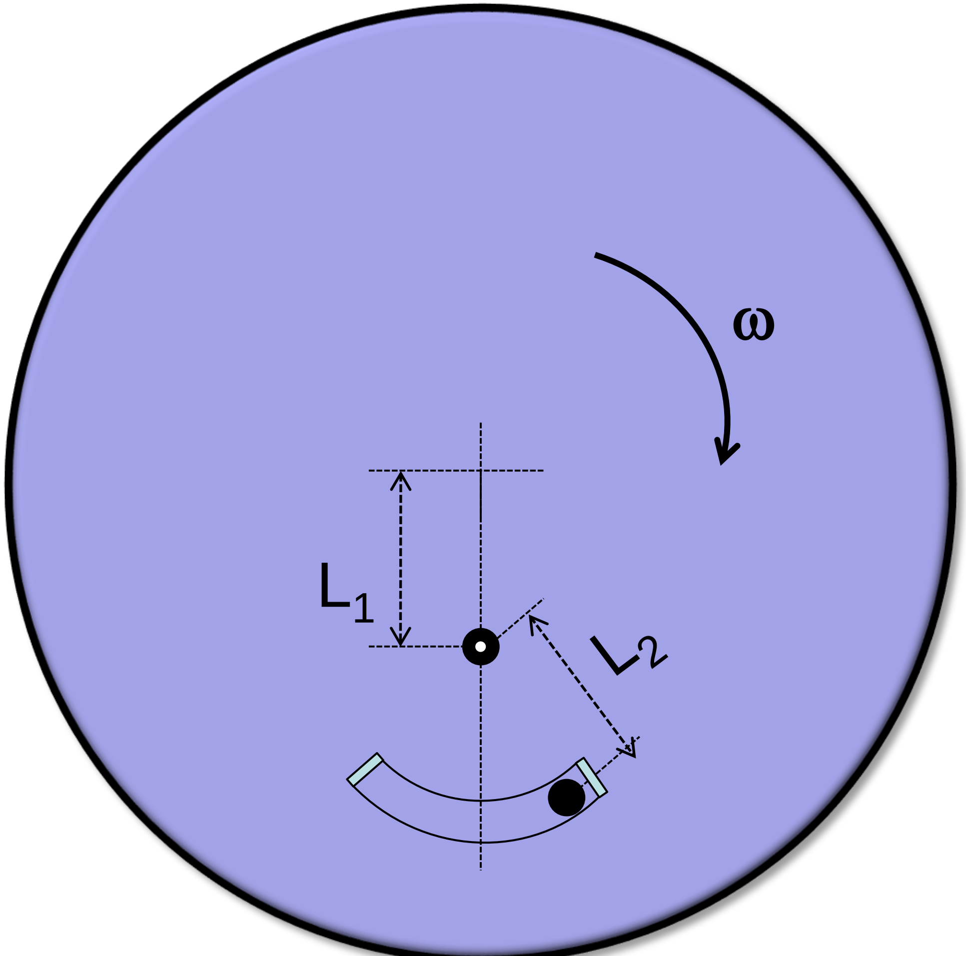
Self-tuning Pendulum System



Rotational inertia	$I = mL_2^2$
Torque on pendulous mass	$\tau = F_t L_2 = m\omega^2 L_1 L_2 \theta_2$
Effective rotational stiffness	$K_\theta = \dfrac{\partial \tau}{\partial \theta_2} = m\omega^2 L_1 L_2$
Pendulum resonant frequency	$\omega_n = \sqrt{\dfrac{K_\theta}{I}} = \omega \sqrt{\dfrac{L_1}{L_2}}$

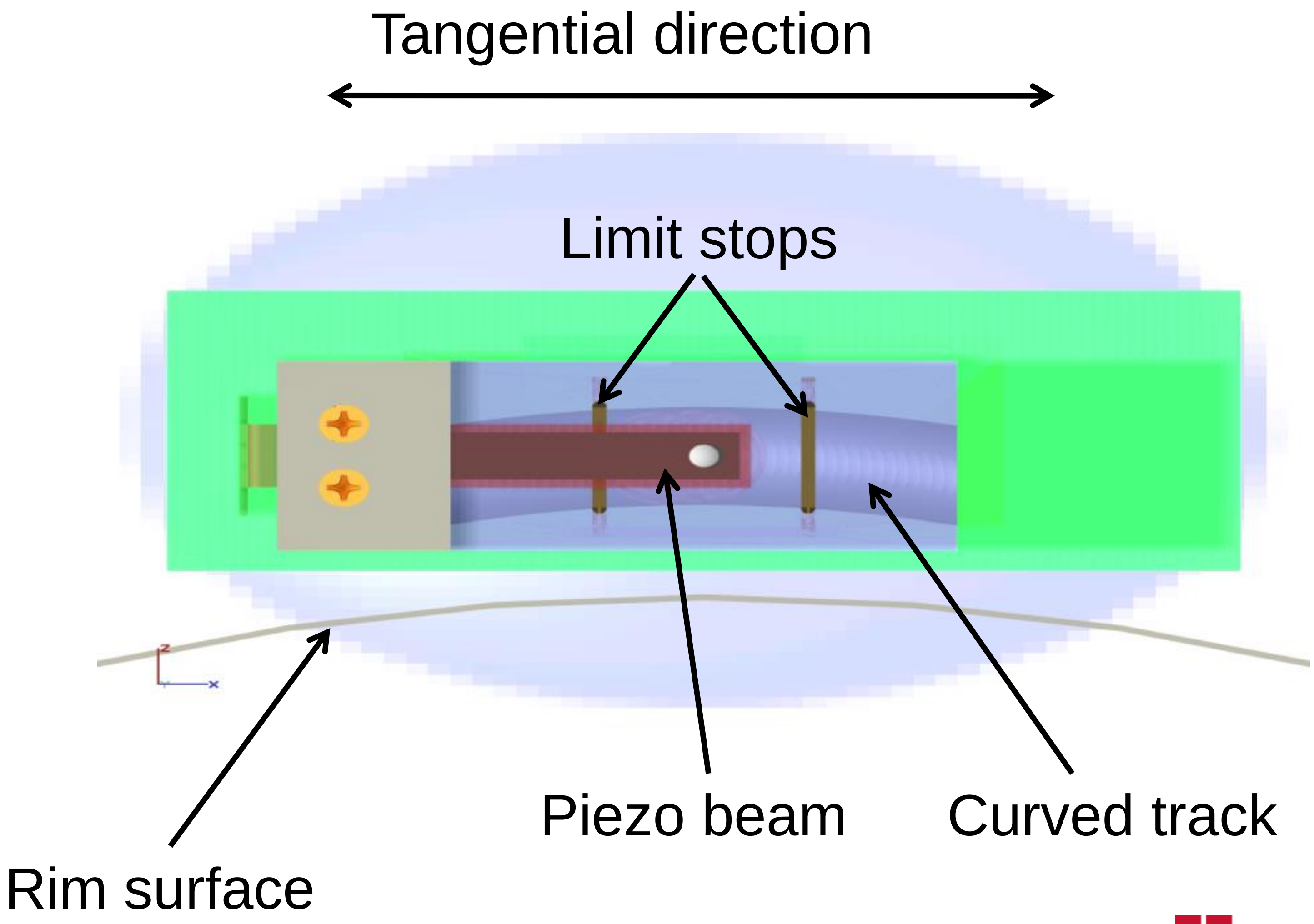
Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

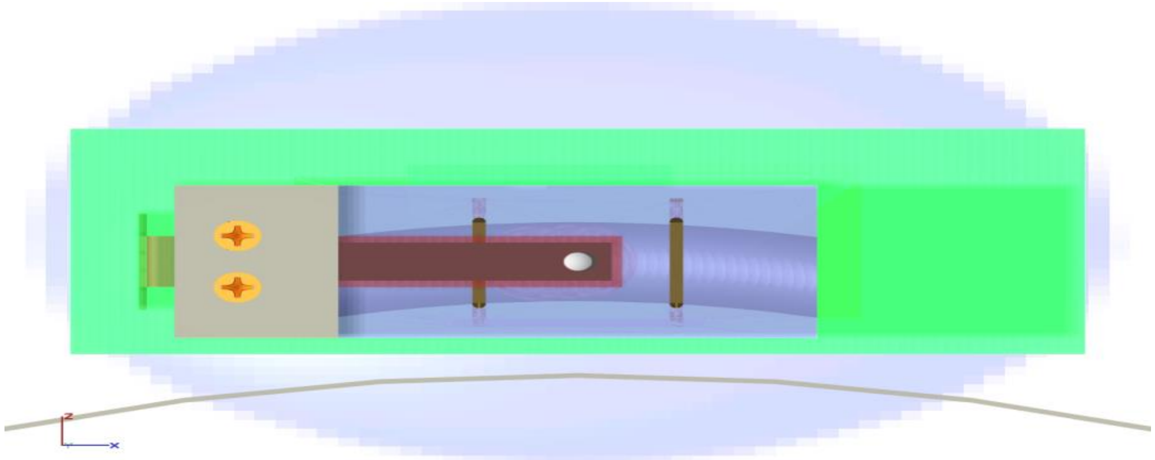
Self-tuning Track System

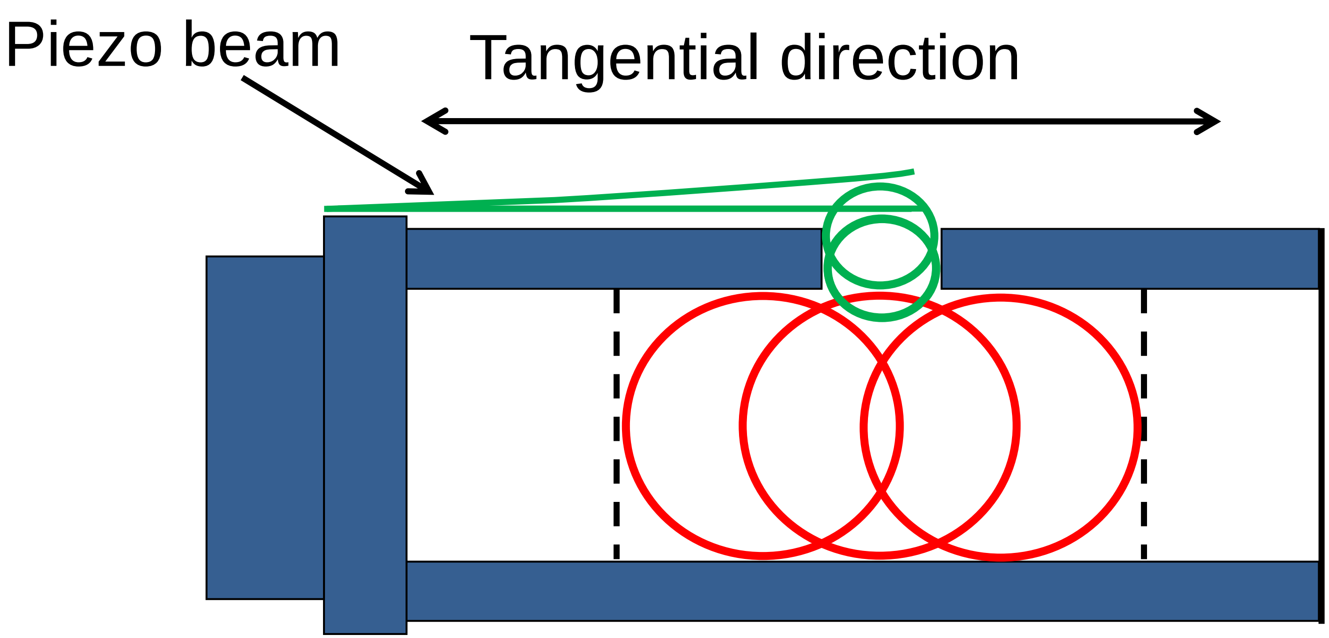


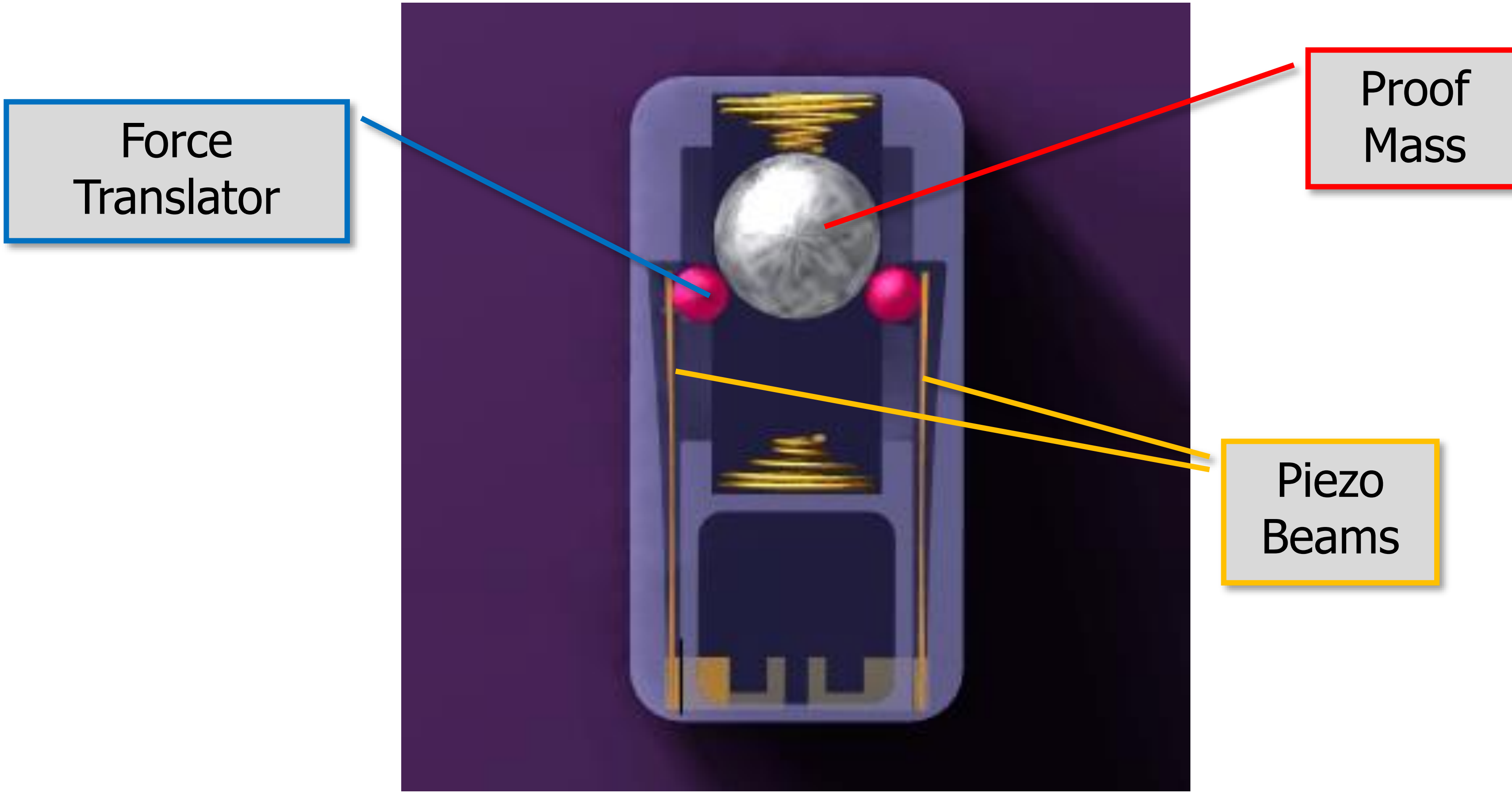
- Pendulum is not practical for a car tire
- Track with radius of L_2 and center of rotation L_1 from wheel center performs same function

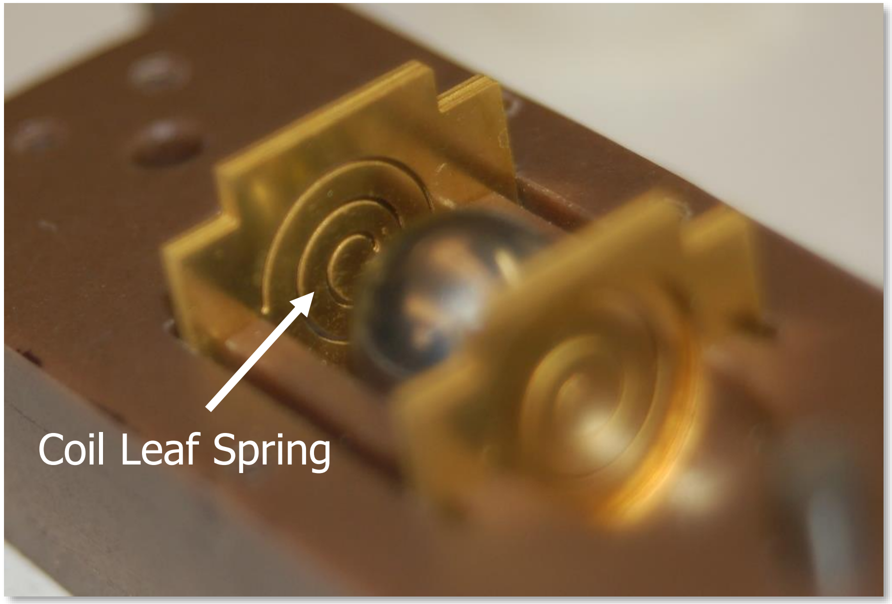
Prototype Concept

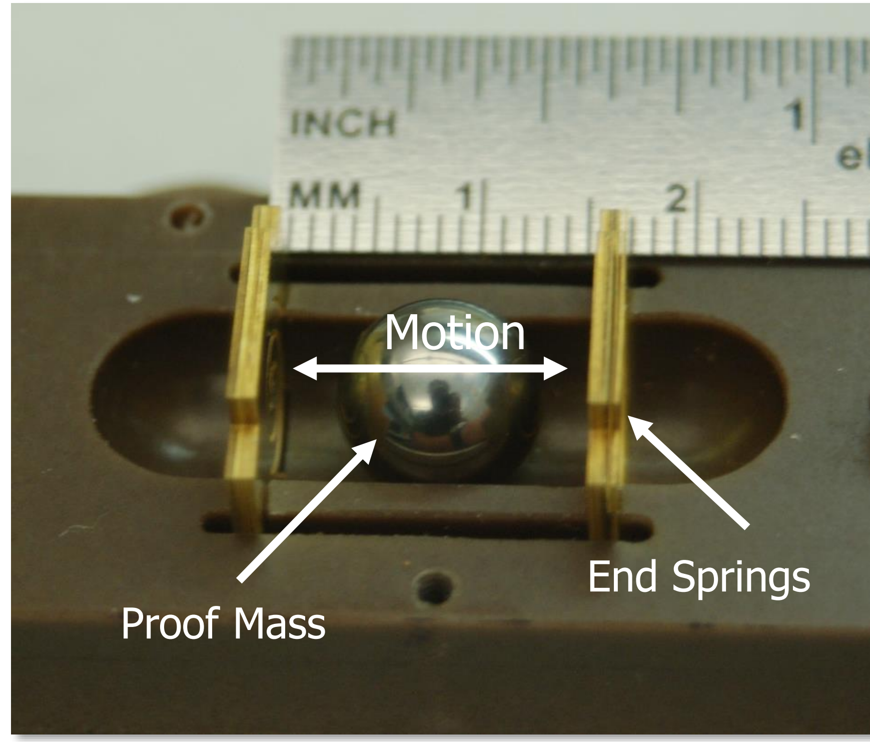


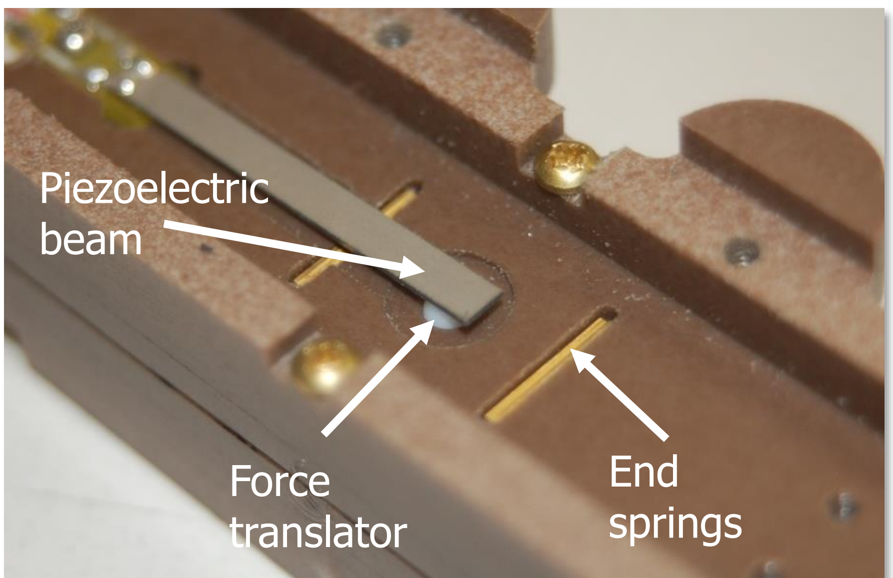


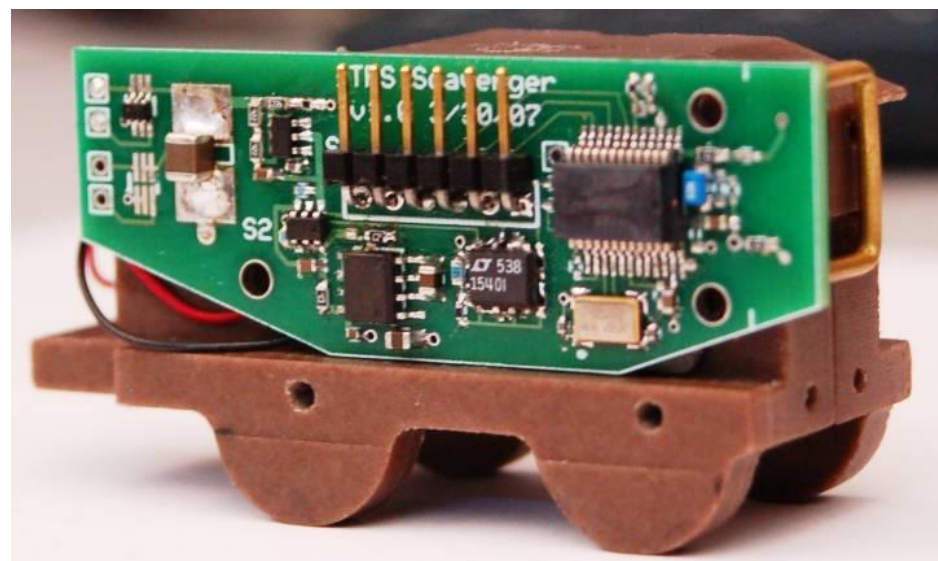

Piezo beam
Tangential direction


Force Translator
Proof Mass
Piezo Beams

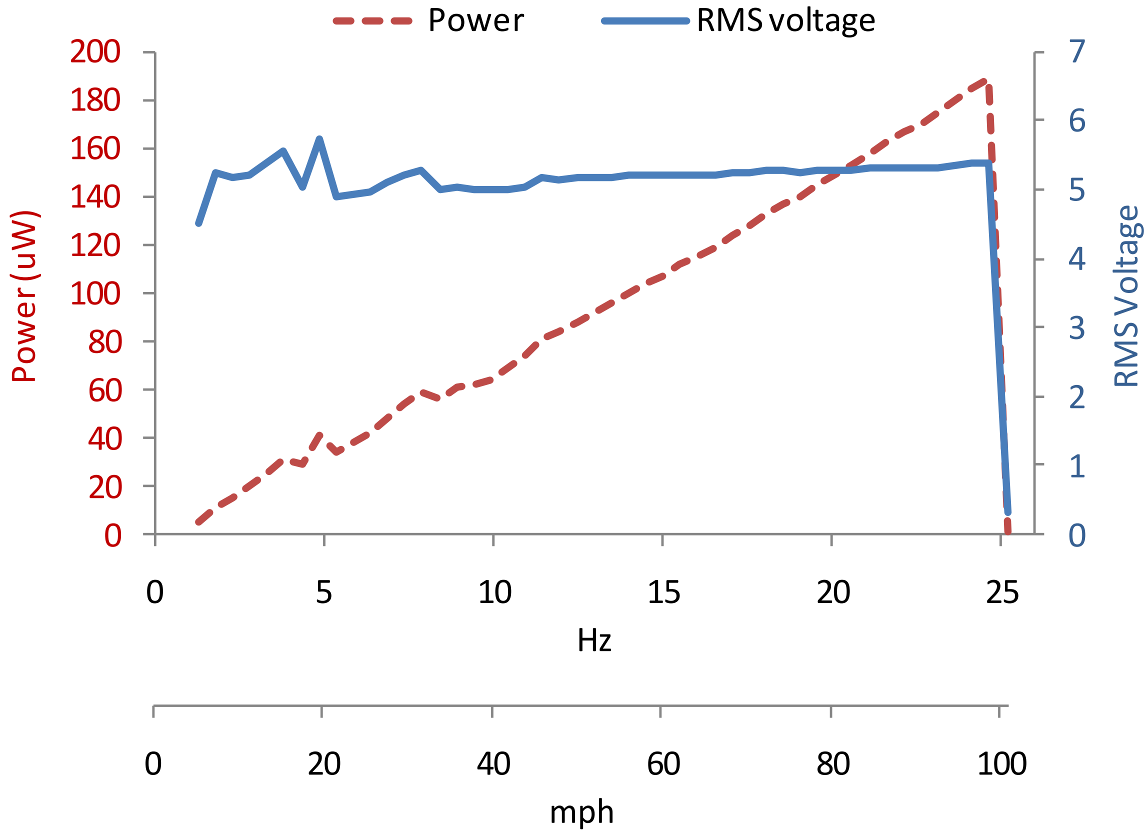

Coil Leaf Spring


INCH
MM
Motion
Proof Mass
End Springs

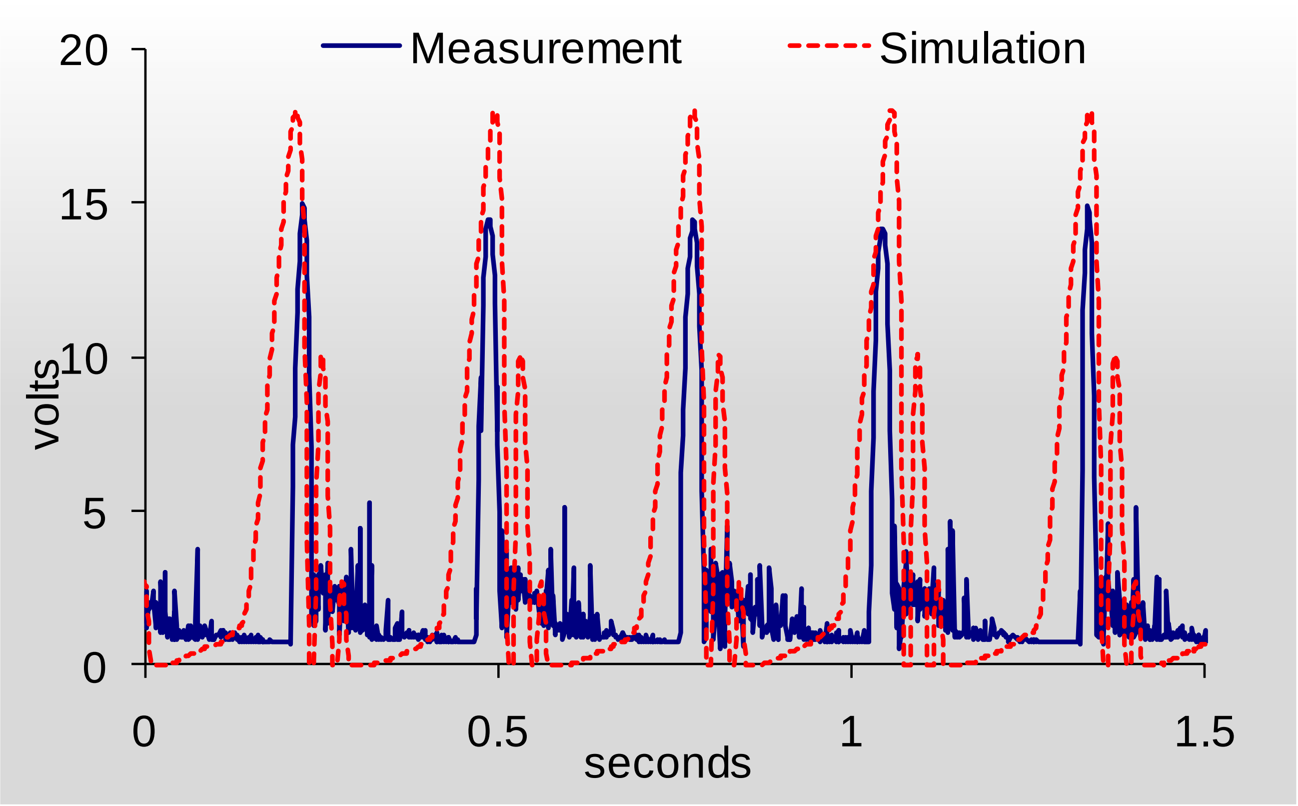

Piezoelectric beam
Force translator
End springs



Simulation Output

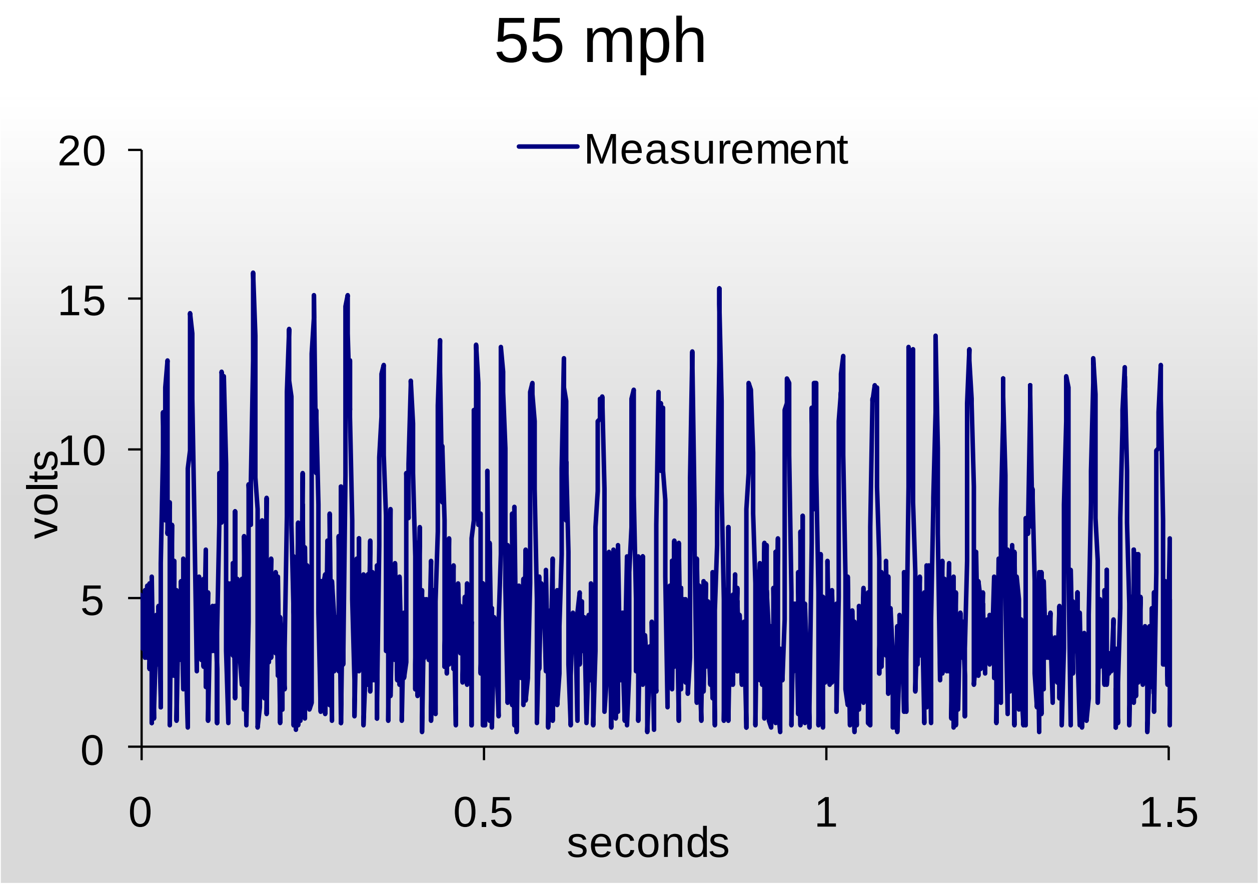


Test Stand Results

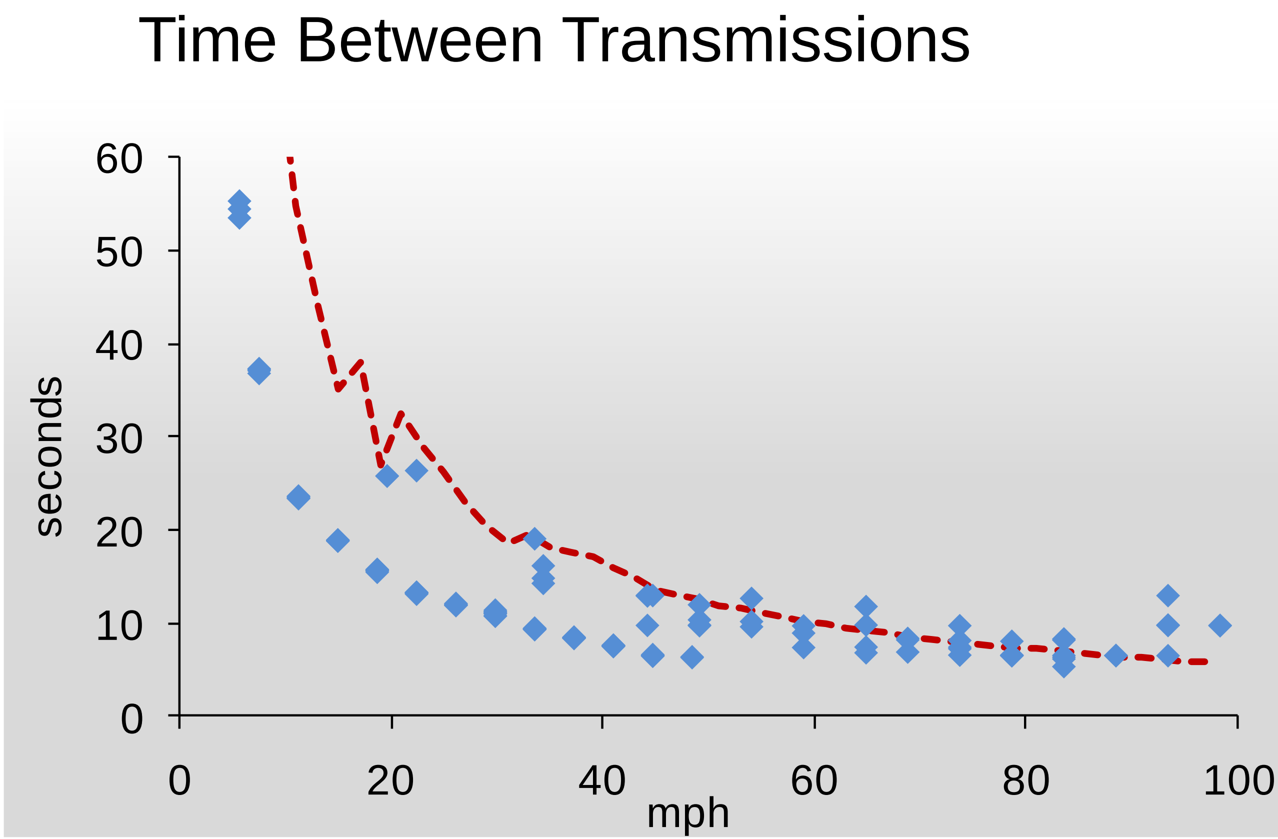


Department of Mechanical Engineering
College of Engineering | The University of Utah

Test Stand Results



Road Test Results



ENERGY HARVESTING FOR WEARABLES

Heel Strike - Shoes

Krupenkin and Taylor. 2011 Nature Communications

Claim 1 watt nominal power

See also http://www.instepnanopower.com/

Heel Strike - Shoes

http://www.energyharvesters.com/

Claim 1 watt nominal power (also)

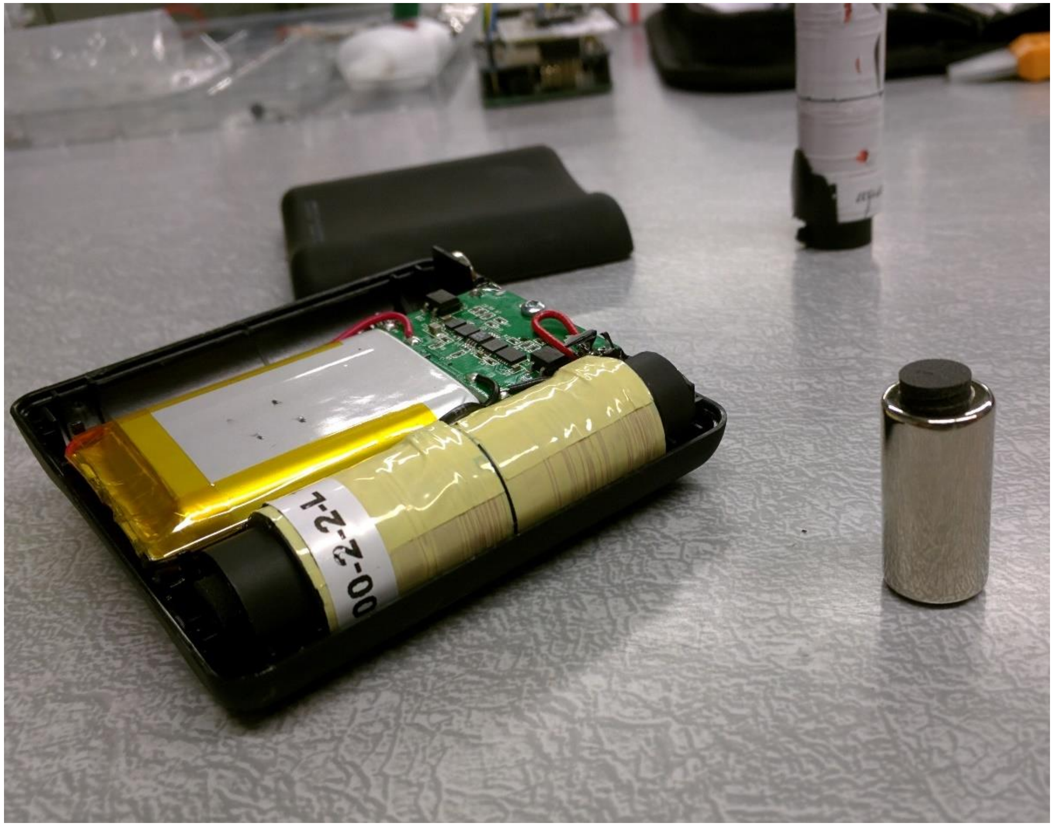
Underlying technology does not seem to be disclosed

And, many others like this

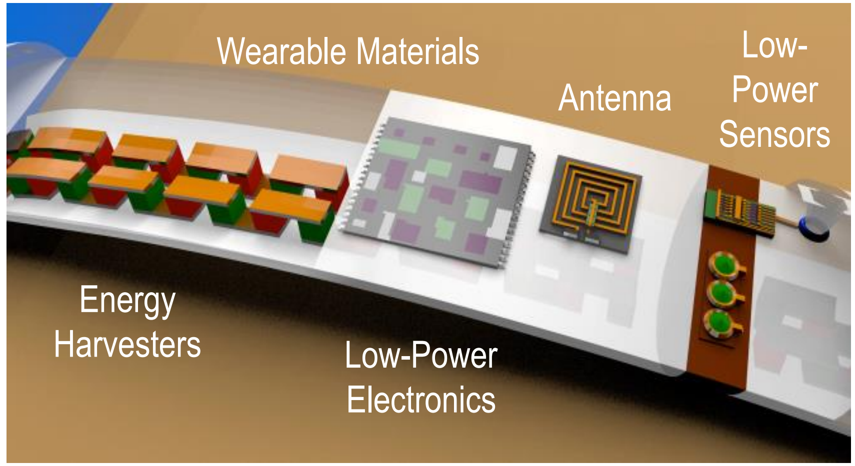
Inertial Harvesters Worn on Body

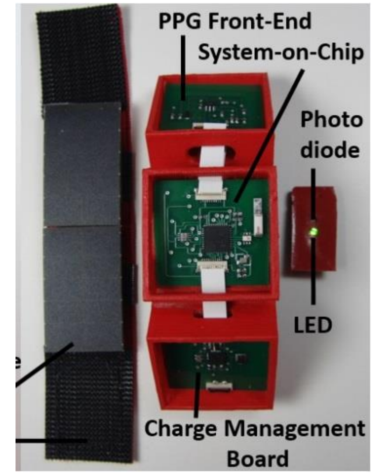
- http://www.getampy.com/
- "An hour of exercise can produce up to 1 hour smart phone battery life."
- My own testing falls very far short of this.

Inertial Harvesters Worn on Body

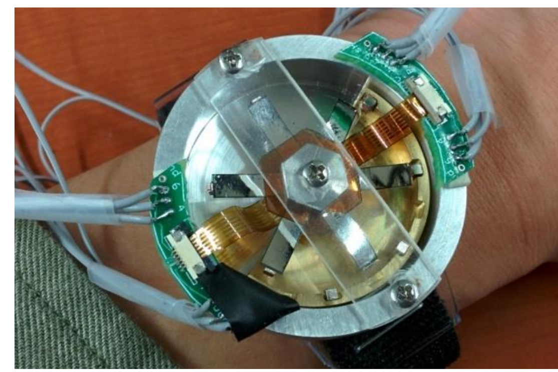


Energy Harvesting for Wearables





SSIST



- Cleary a big market where power sources are important
- What role can / will inertial energy harvesting play?

Standard Quartz Watch
< 10 uW

Jawbone UB4

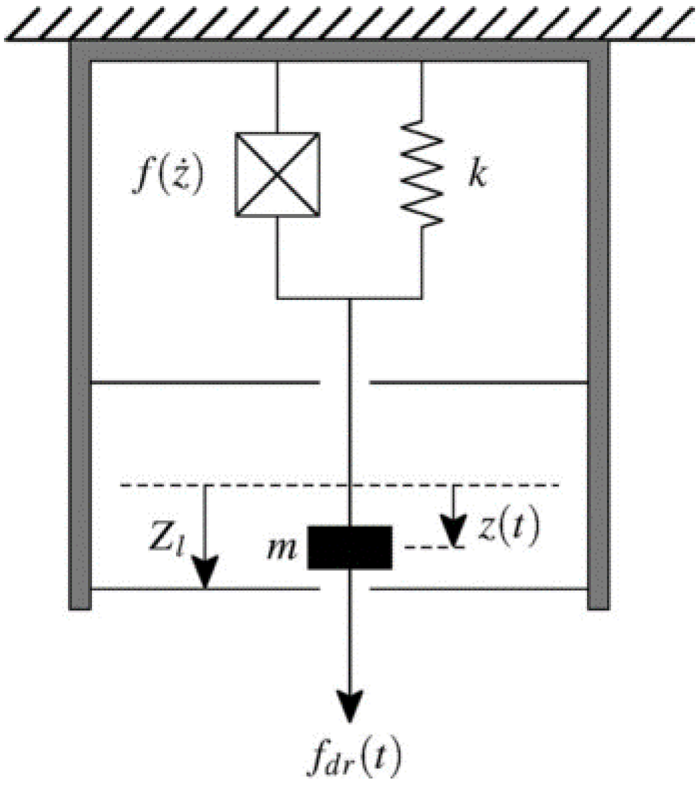
- Battery: 38 mAh, 3.6 v = 137 J
- Lasts “up to 7 days”.
- 225 – 500 uW average power draw

Apple Watch (38 mm version)

- Battery: 205 mAh, 3.6 V = 738 J
- Lifetime: 5 – 18 hrs → 14 - 41 mW
- 14 – 41 mW average power draw

Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

How Much Potential Power Is There?

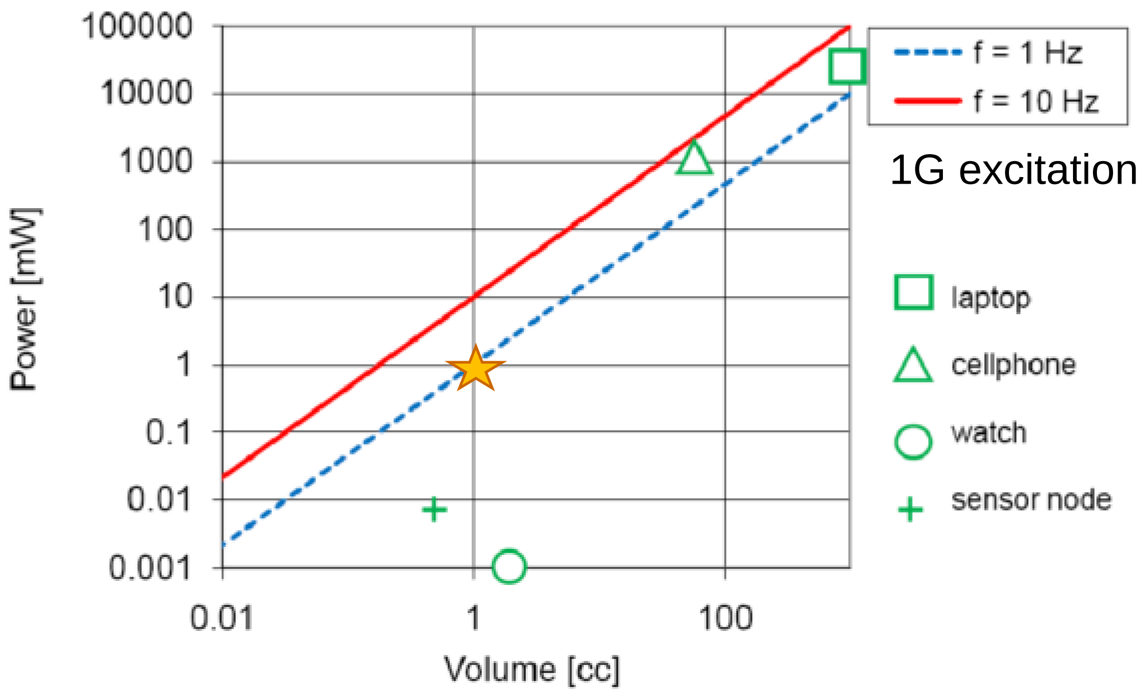


$$P_{max} = \frac{2}{\pi} Y_0 Z_l \omega^3 m$$

Y_0 = excitation amplitude (m)
Z_l = maximum proof mass motion range (m)
ω = excitation frequency (rad/s)
m = proof mass (kg)

Mitcheson, P.D.; et. al. "Energy Harvesting From Human and Machine Motion for Wireless Electronic Devices," in *Proceedings of the IEEE* , vol.96, no.9, pp.1457-1486, Sept. 2008

How Much Potential Power Is There?



- Linear proof mass motion
- Proof mass density = 20 g/cc
- ½ available space taken by proof mass
- Transducer takes no space
- Proof mass motion is "optimally damped"
- 1G continuous excitation

Mitcheson, P.D.; et. al. *Proceedings of the IEEE*, 2008

Rotation Based Energy Harvesters

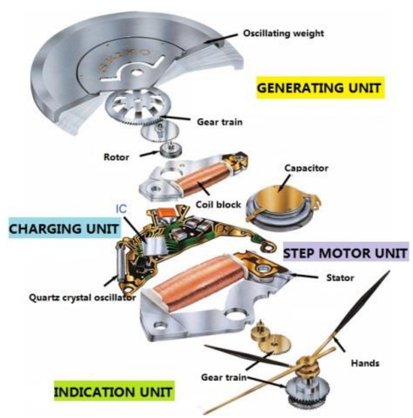
Kinetron generator in Swatch Autoquartz watch

3D drawing of the MGS Watch

400 mJ/day
9.3 uW ave (12 hr day)

Kinetron data sheet

Seiko Kinetic watch

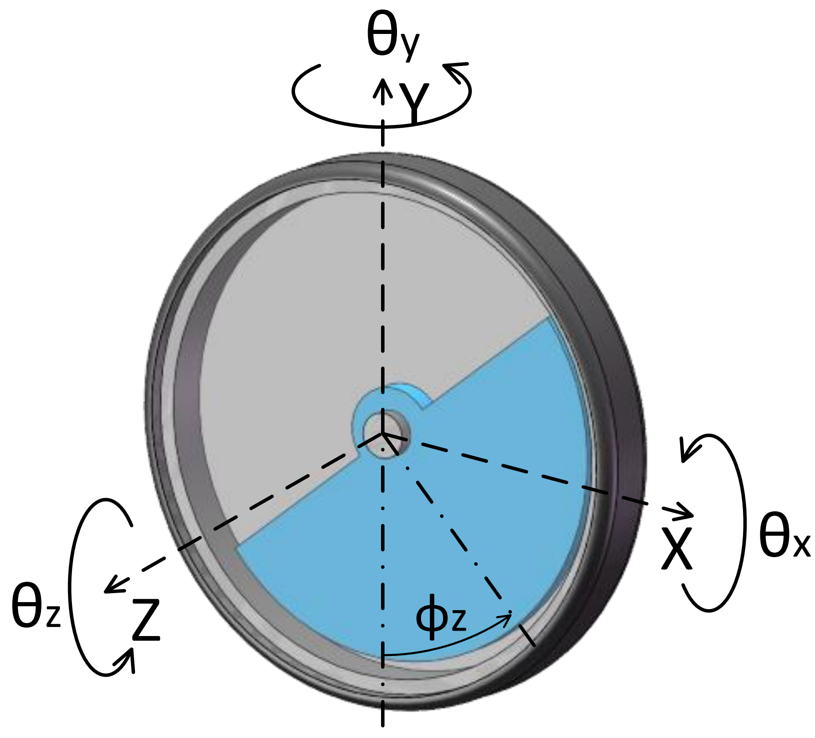


5-10 uW average

Mitcheson, 2010
Paradiso and Starner, 2005

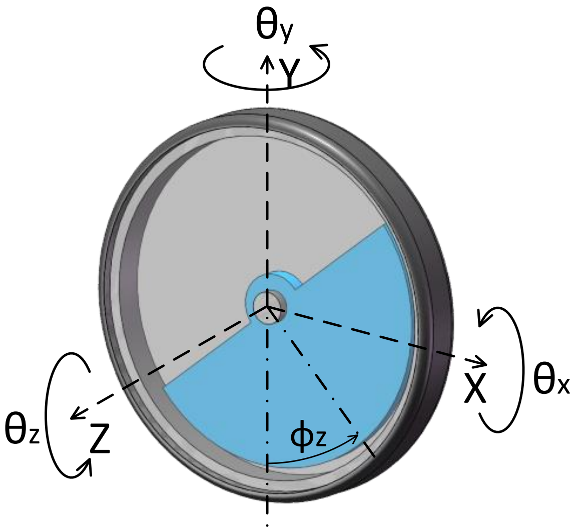
Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

Theoretical Maximum Power



Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

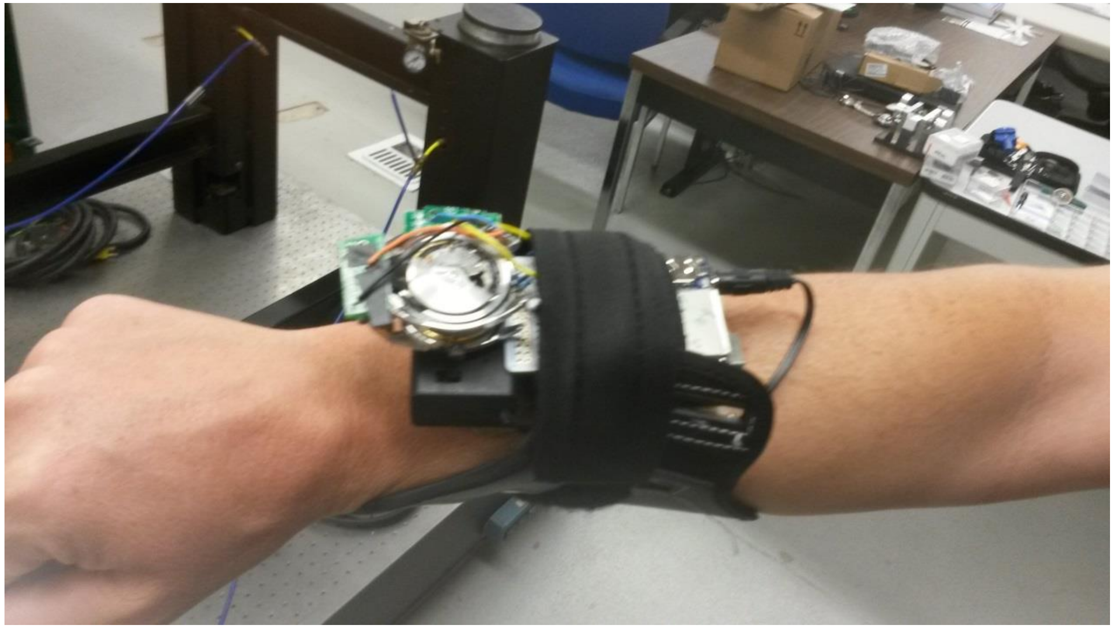
Theoretical Maximum Power

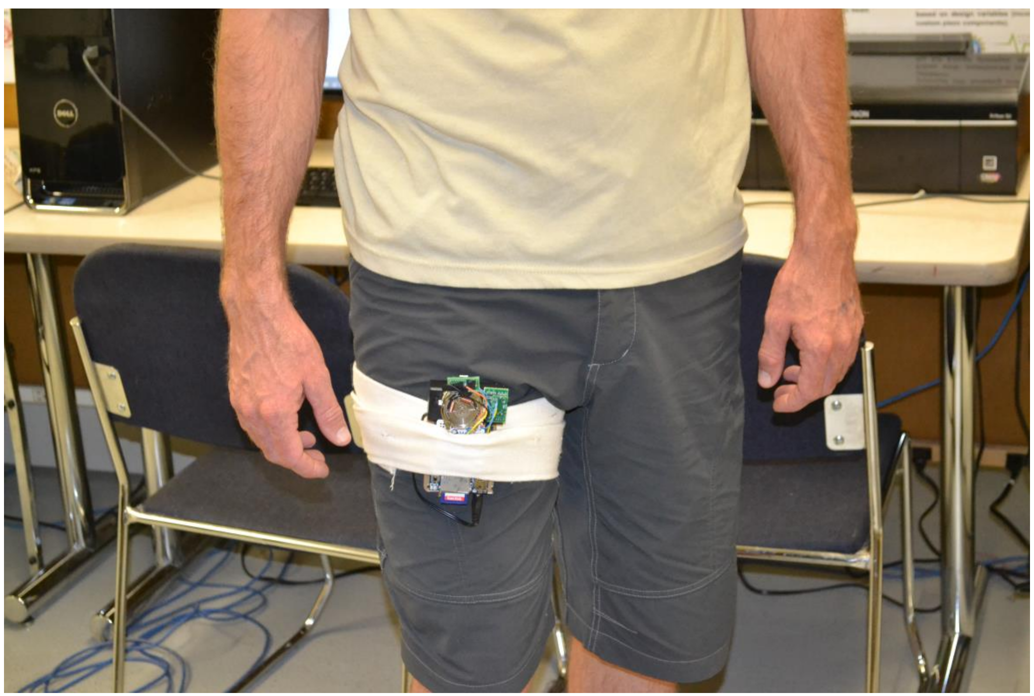


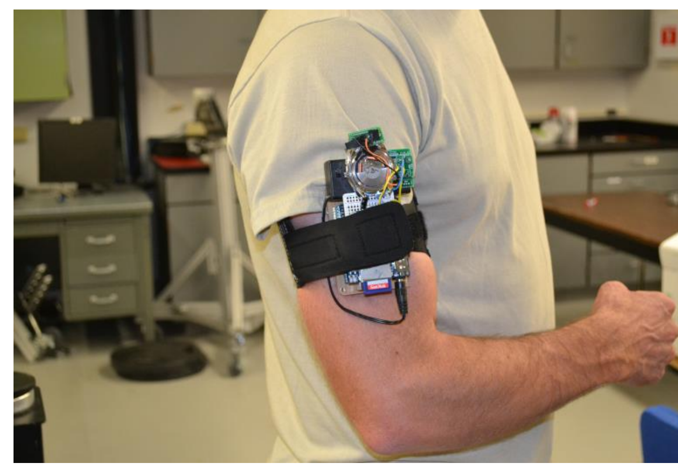
$$m\begin{bmatrix} -l\cos\phi_z \cdot \dot{\phi}_z^2 - l\sin\phi_z \cdot \ddot{\phi}_z \\ -l\sin\phi_z \cdot \dot{\phi}_z^2 + l\cos\phi_z \cdot \ddot{\phi}_z \end{bmatrix} = -m\begin{bmatrix} \ddot{X} \\ \ddot{Y} \end{bmatrix} + \begin{bmatrix} F_x \\ F_y \end{bmatrix} + m\begin{bmatrix} g_x \\ g_y \end{bmatrix}$$

$$I_G\left(\ddot{\theta}_z + \ddot{\phi}_z\right) = -\left(D_e + D_m\right)\dot{\phi}_z + F_x l\sin\phi_z - F_y l\cos\phi_z$$

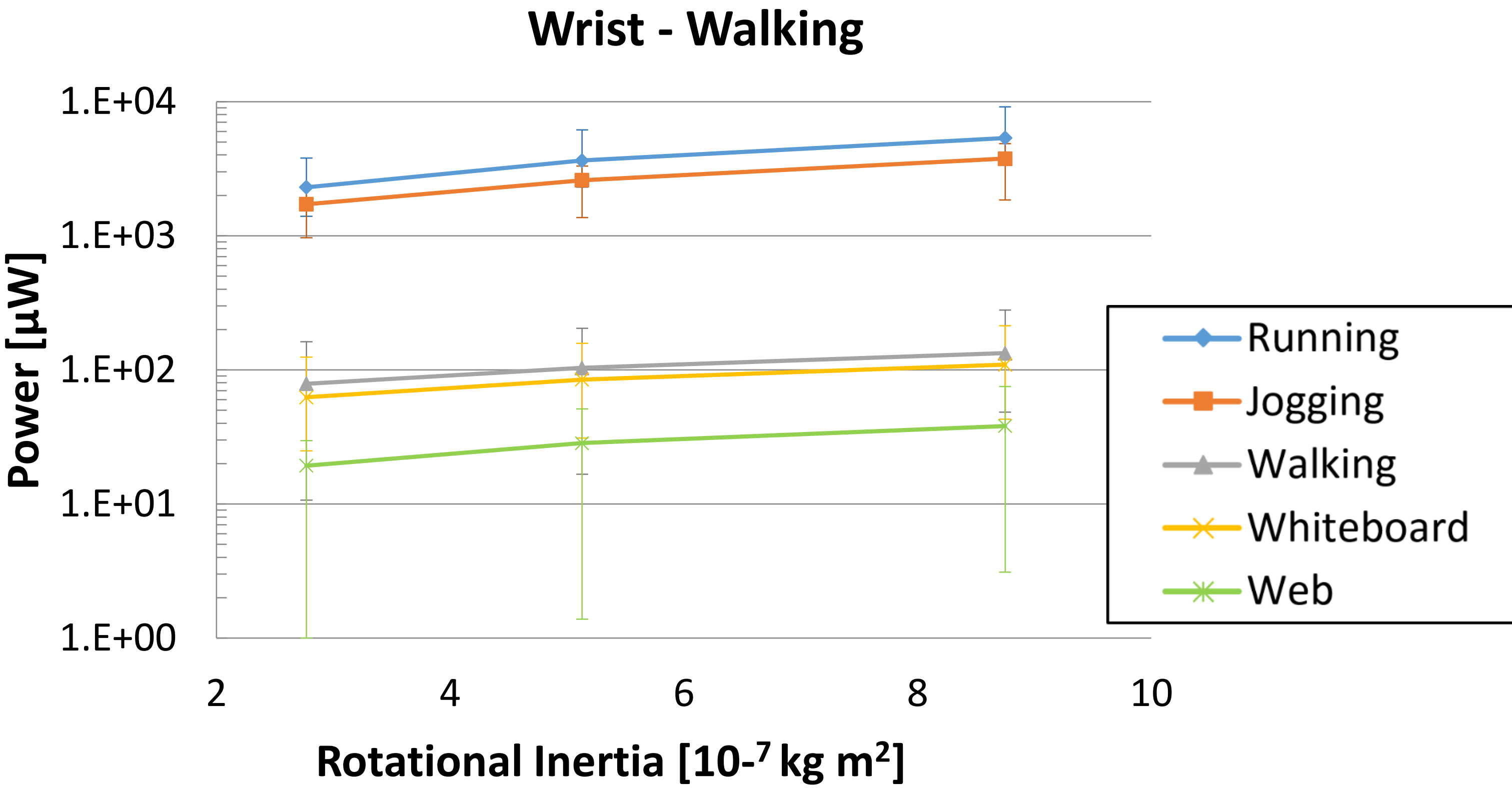
$$P = D_e\dot{\phi}_z^{\;2}$$

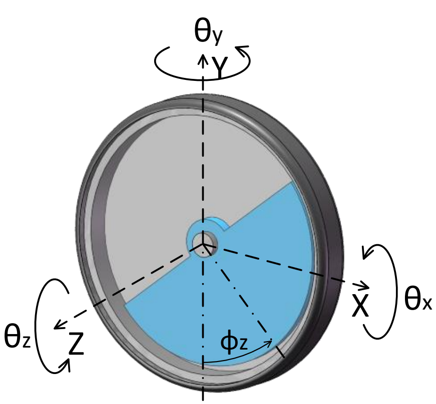






Theoretical Maximum Power



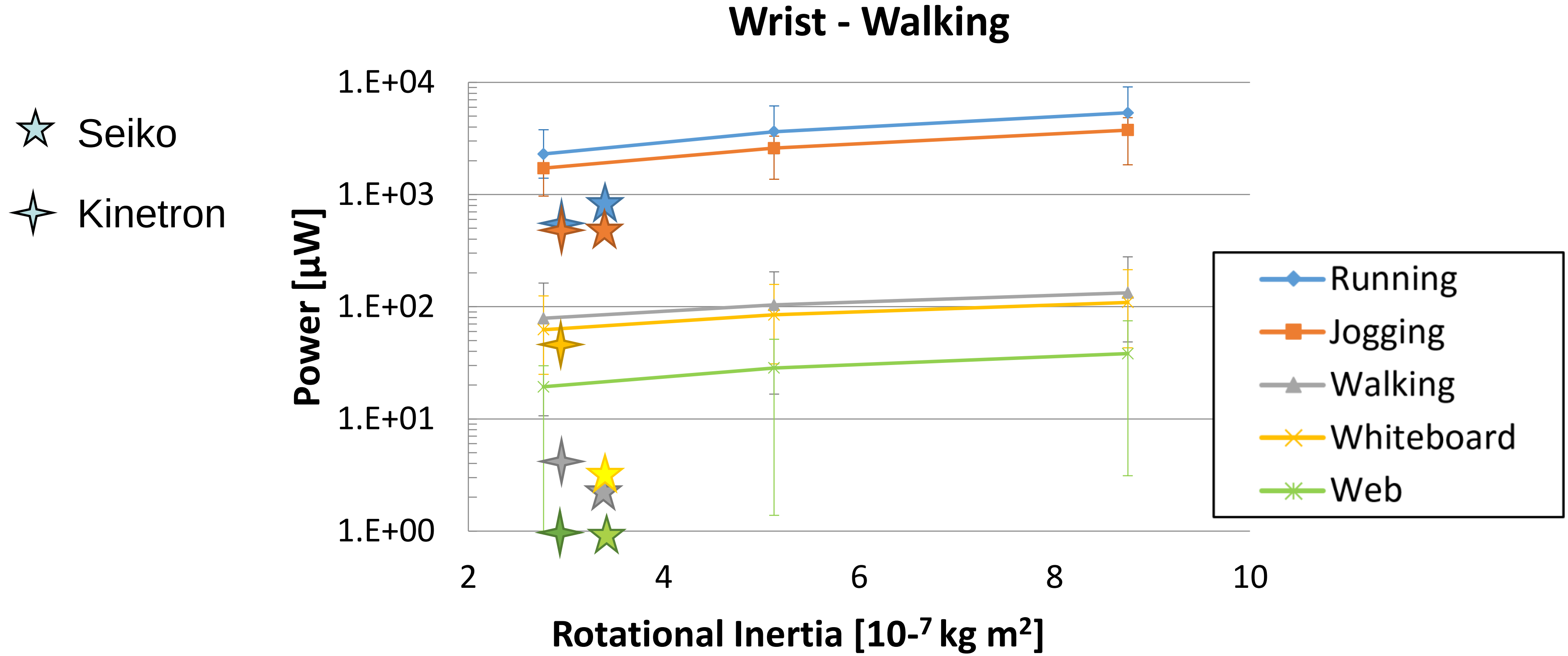


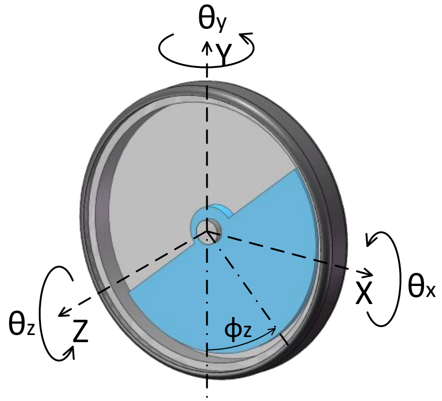
$$m\begin{bmatrix} -l\cos\phi_z \cdot \dot{\phi}_z^2 - l\sin\phi_z \cdot \ddot{\phi}_z \\ -l\sin\phi_z \cdot \dot{\phi}_z^2 + l\cos\phi_z \cdot \ddot{\phi}_z \end{bmatrix} = -m\begin{bmatrix} \ddot{X} \\ \ddot{Y} \end{bmatrix} + \begin{bmatrix} F_x \\ F_y \end{bmatrix} + m\begin{bmatrix} g_x \\ g_y \end{bmatrix}$$

$$I_G\left(\ddot{\theta}_z + \ddot{\phi}_z\right) = -\left(D_e + D_m\right)\dot{\phi}_z + F_x l\sin\phi_z - F_y l\cos\phi_z$$

$$P = D_e\dot{\phi}_z^{\ 2}$$

Theoretical Maximum Power





$$m\begin{bmatrix} -l\cos\phi_z\cdot\dot{\phi}_z^2 - l\sin\phi_z\cdot\ddot{\phi}_z \\ -l\sin\phi_z\cdot\dot{\phi}_z^2 + l\cos\phi_z\cdot\ddot{\phi}_z \end{bmatrix} = -m\begin{bmatrix} \ddot{X} \\ \ddot{Y} \end{bmatrix} + \begin{bmatrix} F_x \\ F_y \end{bmatrix} + m\begin{bmatrix} g_x \\ g_y \end{bmatrix}$$

$$I_G\left(\ddot{\theta}_z + \ddot{\phi}_z\right) = -\left(D_e + D_m\right)\dot{\phi}_z + F_x l\sin\phi_z - F_y l\cos\phi_z$$

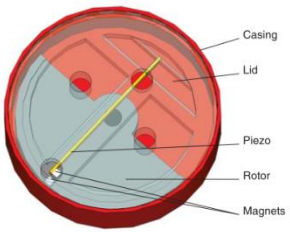
$$P = D_e\dot{\phi}_z^{\,2}$$

Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

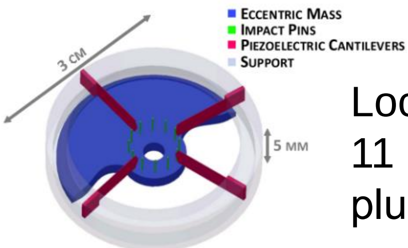
Where Is the Potential for Improvement?

- Watches have relatively high total (mechanical + electrical) damping with $D_e >> D_m$
- Must overcome static friction / damping under low excitation to start generating much energy.
  - Underperform during walking.
- Other inefficiencies
  - 40% efficiency between energy stored in intermediate spring and electrical power output
- Don’t take advantage of potentially beneficial dynamics (i.e. springs and resonance)

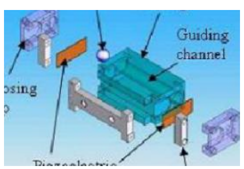
Theoretical Maximum Power



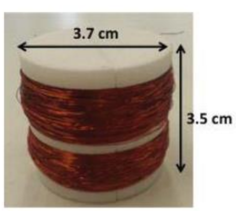
Pillatsch, et.al. 2013
7 uW - Jogging



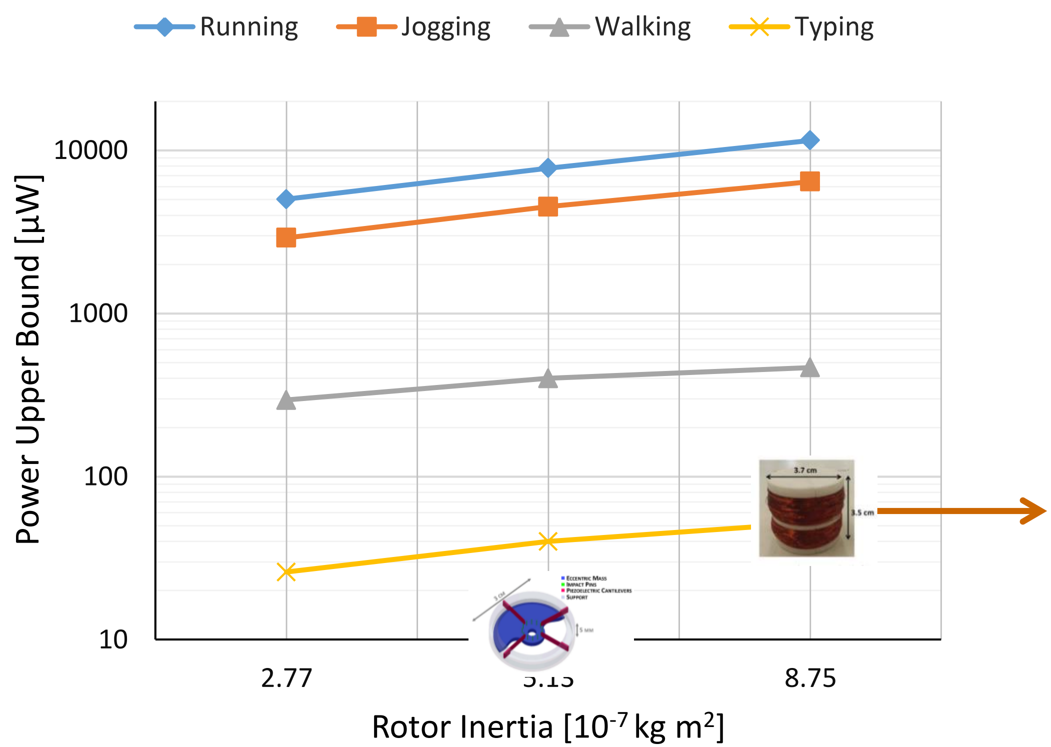
Lockhart, et.al. 2014
11 uW – “Continuous plucking”



Renauld, et.al. 2009
47 uW – “Continuous rotation”

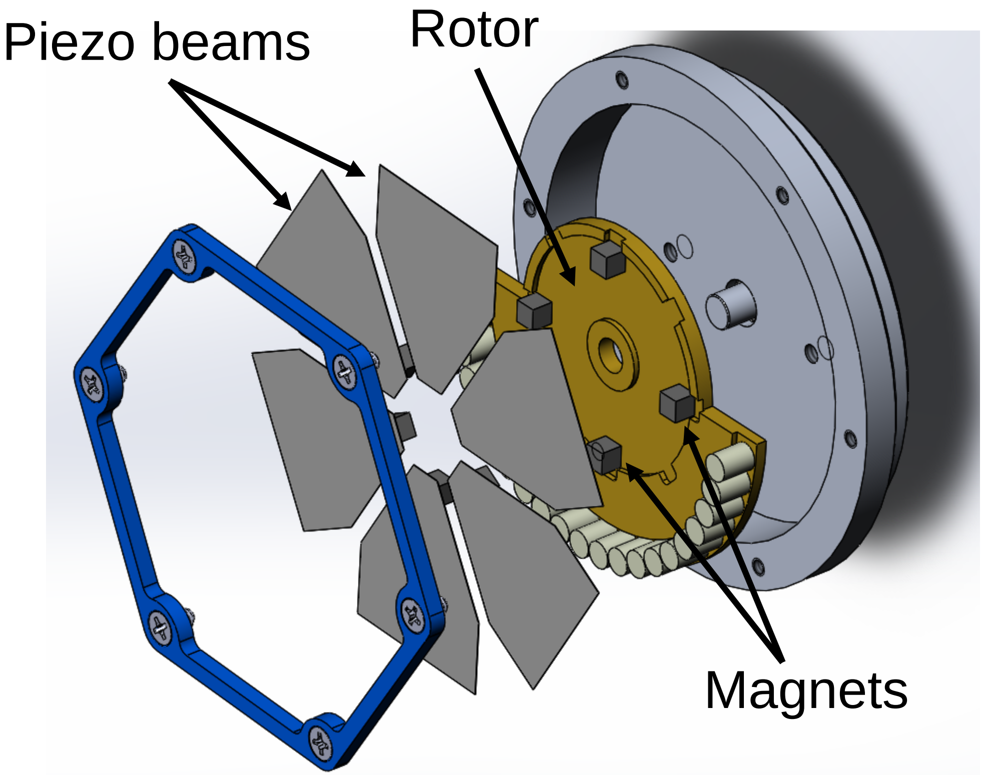


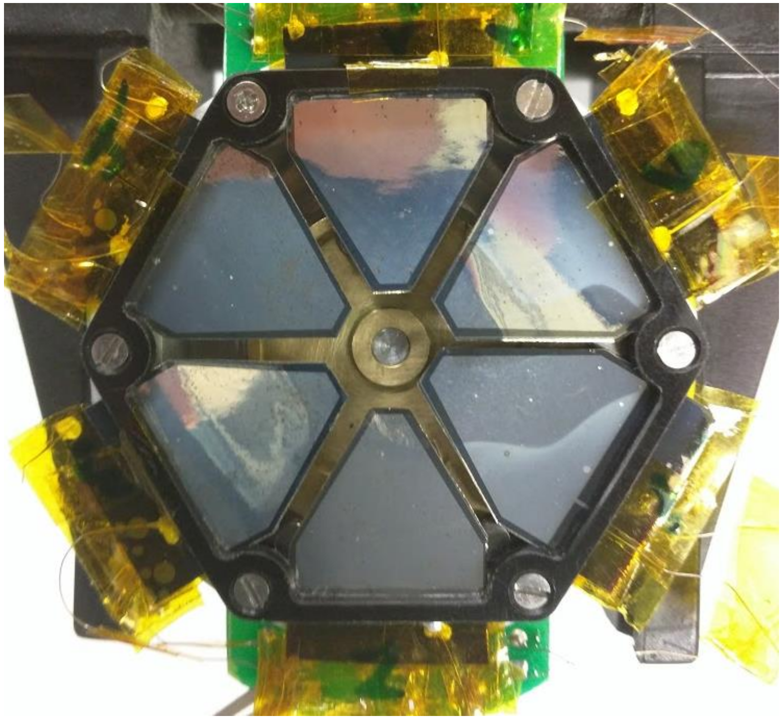
Rao, et.al. 2013
100 uW – jogging
33 uW - walking



Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

Piezo / Magnetic Harvester

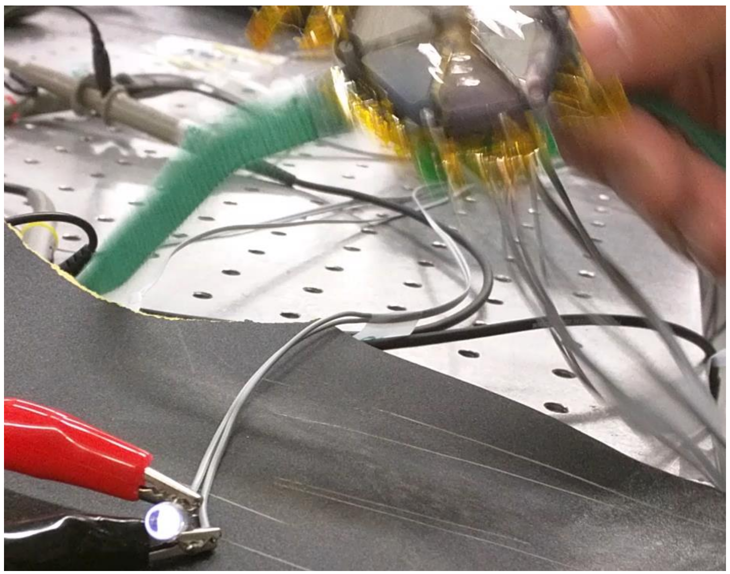


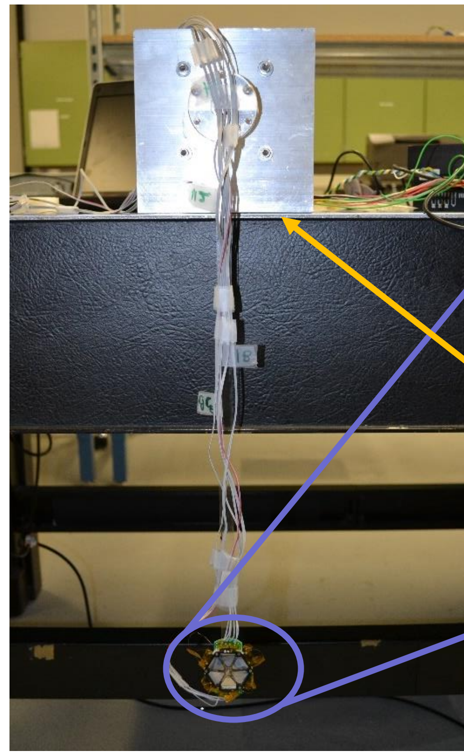


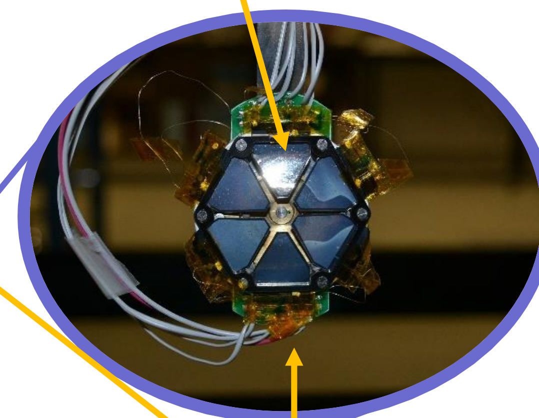
Prototype and Test Results

Custom fabricated thinfilm PZT

PENNSTATE



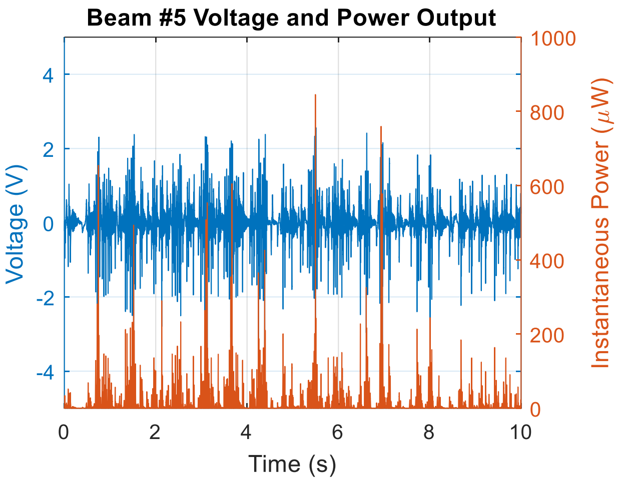




System design, and testing

THE UNIVERSITY OF UTAH

Prototype and Test Results



Input		Total Power [μW]	Total Power [μW] (best* X12)
Swing Arm $30 \sin \frac{2\pi t}{T}$	T=1s	10.3	41.8
On Wrist	Jogging in place	38.3	156.6
	Rotating the wrist	25.1	91.4
Shaking in hand	Rotor in continuous rotation	37.8	158.8

* Best performing beam shown above, which is a single electrode (i.e. unimorph). Assumes beams perform at this equivalent level.

Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

Conclusions

- There is about 1 order of magnitude gap between what current COTS (and research) devices provide (~ 10 uW) and what wearable systems need (~ 100 uW)
- Theory indicates that it is possible to close that gap in a ~ cm^3 size device … but technological solutions will need to be developed that approach the theoretical maximum
- Eccentric rotor based devices are promising … but there may be other approaches that could get closer to the theoretical maximum

Acknowledgements

This work was supported by the National Science Foundation ASSIST Nanosystems ERC under Award Number EEC-1160483

- Prof's Susan Trolier-McKinstry, Tom Jackson, and Chris Rahn at Penn State
- PhD Students
  - Tiancheng Xue (U of Utah), Charlie Yeager (Penn St.), Hong Goo Yeo (Penn St.), Xiaokun Ma (Penn St.)