# Energy Harvesting: advanced MEMS to NEMS

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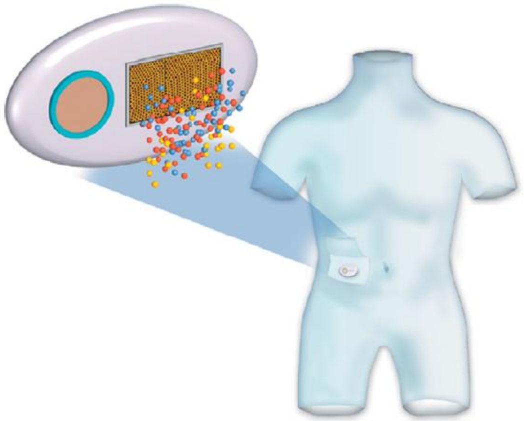
# Outline

- MEMS- to NEMS-based energy harvesters and potential applications
- Micro/nanoscale energy harvesters: scaling issues
- Nonlinear and frequency-up conversion approaches
- Conclusions

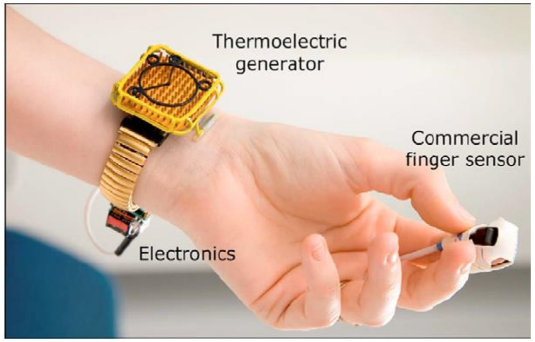
# MEMS- to NEMS-based harvesting devices and potential applications

## MEMS-based drug delivery systems



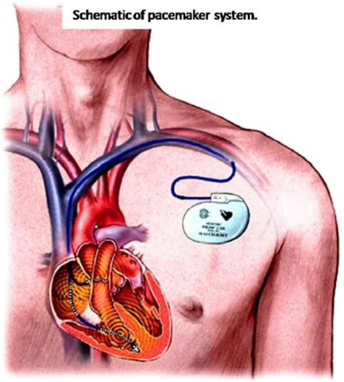
Bohm S. et al. 2000

## Body-powered oximeter




Leonov, V., & Vullers, R. J. (2009).

## Heart powered pacemaker




D. Tran, Stanford Univ. 2007

Pacemaker consumption is around **40uW**.

Beating heart could produce **200uW** of power from heat differentials, physiological pressures, and flows and movements, such as blood flow

## Micro-robot for remote monitoring

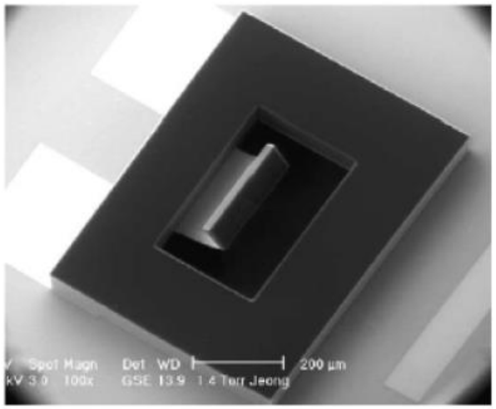
A. Freitas Jr., Nanomedicine, Landes Bioscience, 1999

A 1mm-20mg nanorobot flying at 1 m/s requires F ~ 4 microN and **P ~ 41 uW.**

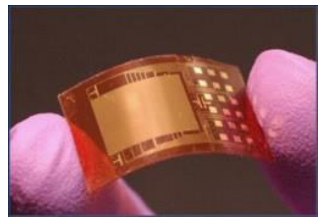
The input power for a 20mg robotic fly is **10 – 100 uW** depending on many factors: air friction, aerodynamic efficiency etc.

# MEMS- to NEMS-based harvesting devices and potential applications

## Piezoelectric

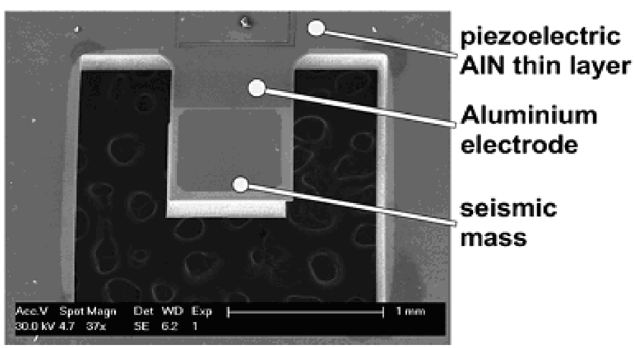



Jeon et al. 2005

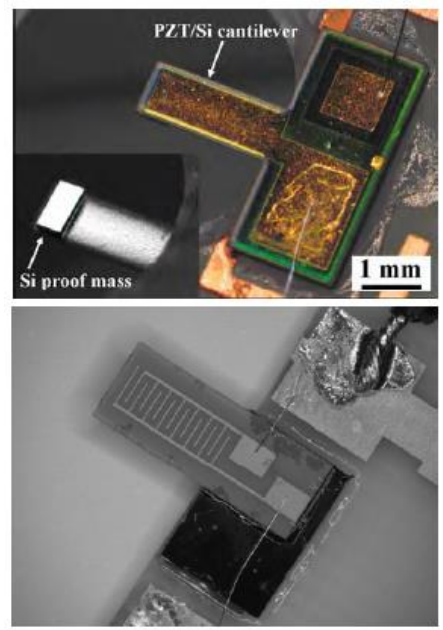


ZnO nanowires
Wang, Georgia Tech
(2005)

Chang. MIT 2013



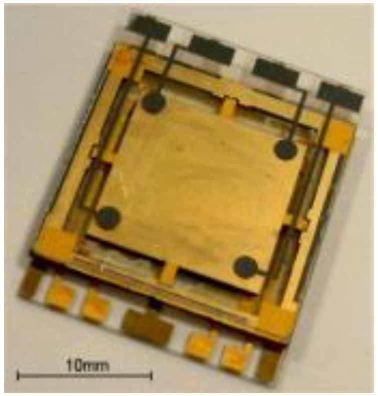

M. Marzencki 2008 – TIMA Lab (France)



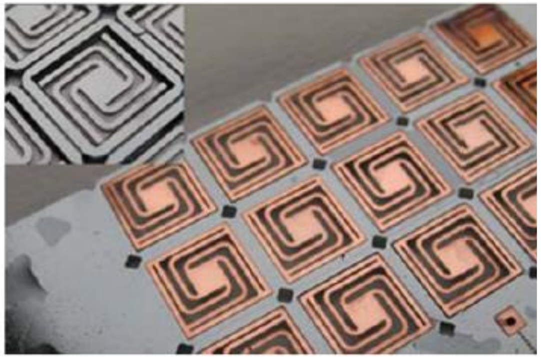

D. Briand, EPFL 2010

# MEMS- to NEMS-based harvesting devices and potential applications

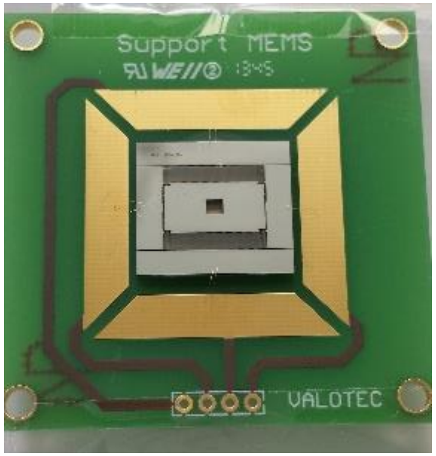
**Electrostatic and Electromagnetic**



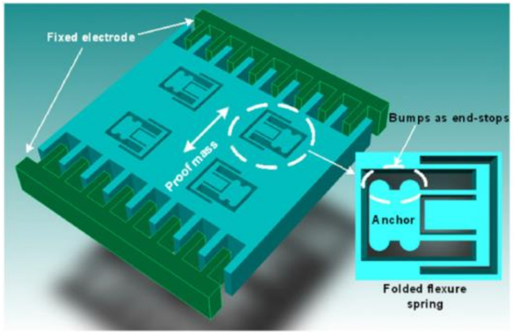

Mitcheson 2005 (UK)
Electrostatic generator 20Hz
2.5uW @ 1g



EM generator, Miao et al. 2006



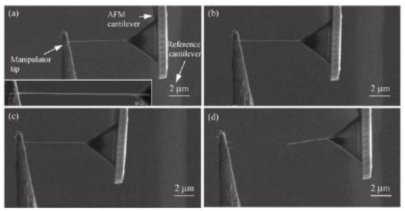

Cottone F., Basset P.
ESIEE Paris 2013-14



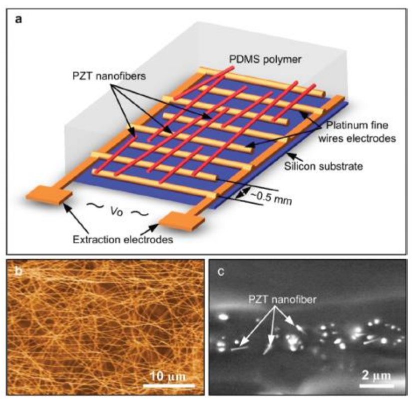

Le and Halvorsen, 2012

# MEMS- to NEMS-based harvesting devices and potential applications

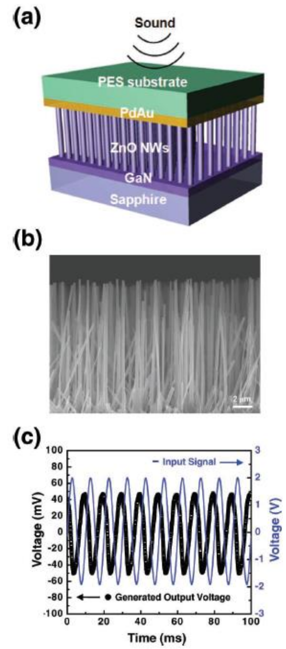
**NEMS-based energy harvesting devices**



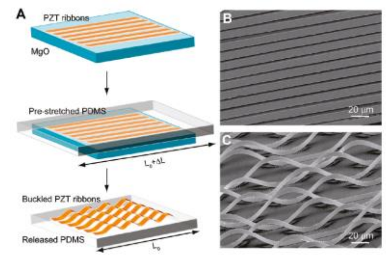

ZnO nanowires –Xu F.
(2010) tensile stress test



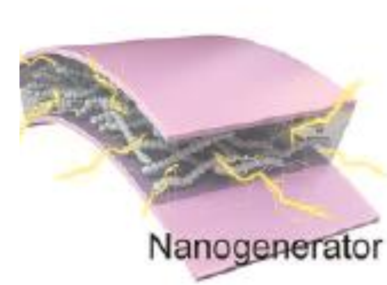

Chen, X. et al (2010) Nano letters
0,6 V – 30nW




Cha, S. (2010). Sound-driven piezoelectric nanowire-based nanogenerators. Advanced materials




Qi, Yi, 2011 Nano Letters
PZT Nanoribbons




Virus-directed BaTiO3 nanogenerator

Jeong, C. et al (2013). ACS nano,

2005 → 2015

**Time**

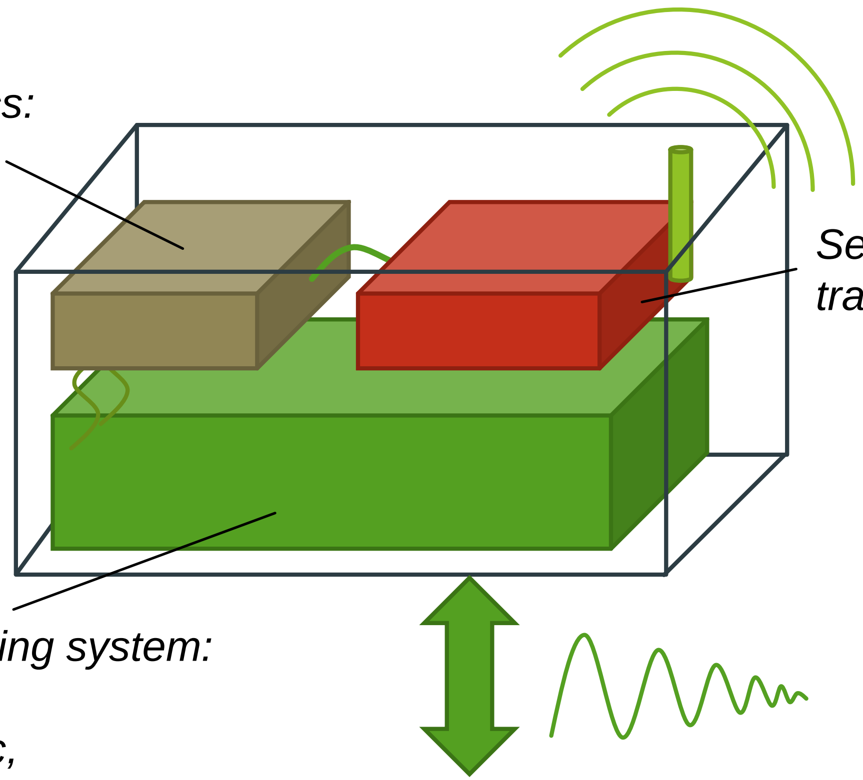
# Microscale kinetic harvesters: scaling issues

**Objective :**

100 μW/cm$^3$ of power density

*Temporary storage*
*and conditioning electrinics:*

- *Ultra capacitors*
- *Rechargeable Batteries*



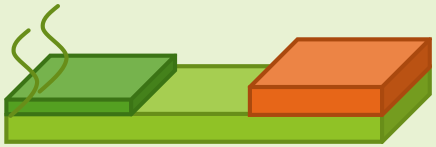
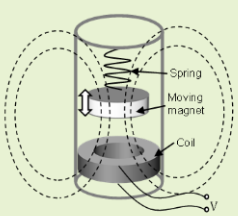
*Sensor node and transceiver*

*Energy harvesting system:*

- *piezoelectric,*
- *electromagentic,*
- *electrostatic,*
- *magnetostrictive*

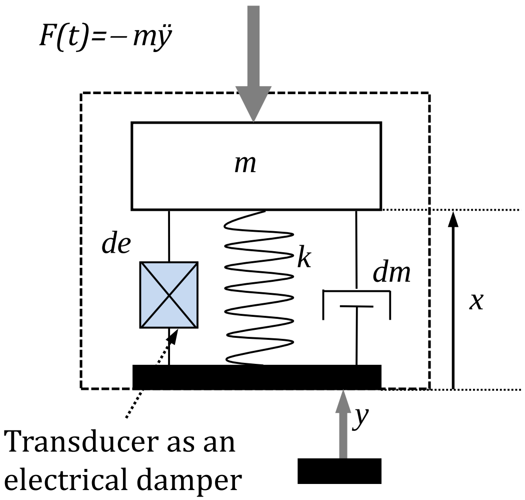
*Mechanical vibrations*

# Who’s the best for MEMS/NEMS ?

| Technique | Advantages | Drawbacks |
|---|---|---|
| **Piezoelectric**  | • high output voltages<br>• well adapted for miniaturization<br>• high coupling in single crystal<br>• no external voltage source needed | • expensive<br>• small coupling for piezoelectric thin films<br>• large load optimal impedance required (MΩ)<br>• Fatigue effect |
| **Electrostatic**  | • suited for MEMS integration<br>• good output voltage (2-10V)<br>• possiblity of tuning electromechanical coupling<br>• Long-lasting | • need of external bias voltage<br>• relatively low power density at small scale |
| **Electromagnetic**   | • good for low frequencies (5-100Hz)<br>• no external voltage source needed<br>• suitable to drive low impedances | • inefficient at MEMS scales: low magnetic field, micro-magnets manufacturing issues<br>• large mass displacement required. |

# Microscale kinetic harvesters: scaling issues

First order power calculus with William and Yates model




Motion equation

$$m\ddot{x}(t)+(d_m+d_e)\dot{x}(t)+kx(t)=-m\ddot{y}(t)$$

Inertial force

$$f(t)=-m\ddot{y}=Y_0\sin(\omega t)$$

$$x(t)=\frac{\omega^2}{\sqrt{\left(\frac{k}{m}-\omega^2\right)^2+\left(\frac{(d_e+d_m)\omega}{m}\right)^2}}Y_0\sin(\omega t-\phi)$$

Steady state solution

setting $d_T=d_m+d_e$ the total damping coefficient, the phase angle $\phi$ is given by

$$\phi=\tan^{-1}\left(\frac{d_T\omega}{k-\omega^2 m}\right)$$

and the natural frequency $\omega_n=\sqrt{k/m}$

By introducing the damping ratio, namely $\zeta_T=(\zeta_e+\zeta_m)=d_T/2m\omega_n$, the position transfer fuction is expressed by

$$H_{xf}(\omega)=\frac{X(\omega)}{Y(\omega)}=\frac{\omega^2}{-\omega^2+2i\omega(\zeta_e+\zeta_m)\omega_n+\omega_n^2}$$

# Microscale kinetic harvesters: scaling issues

## First order power calculus with William and Yates model

The instantaneous dissipated power by electrical damping is given by

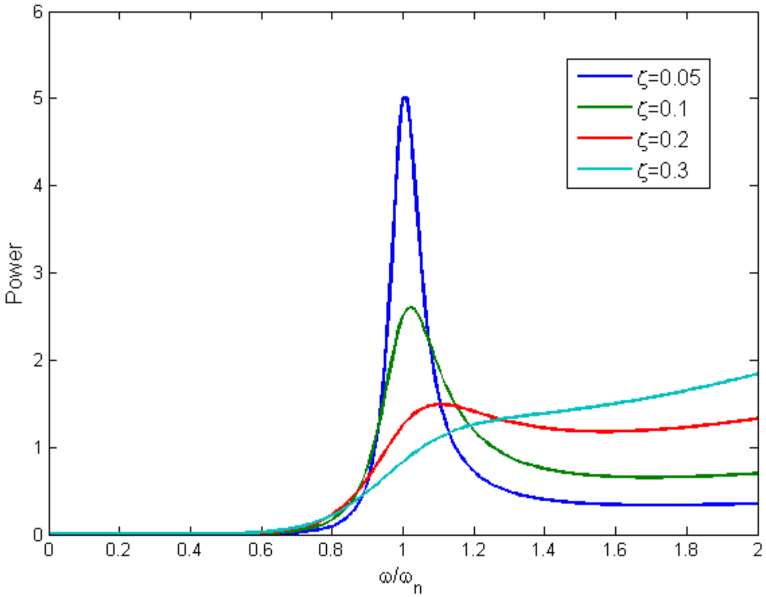
$$P(t) = \frac{d}{dt}\int_0^x F(t)dx = \frac{1}{2} d_T \dot{x}^2$$

The velocity is obtained by the first derivative of steady state amplitude

$$\dot{X} = \frac{\omega r^2 Y_0}{\sqrt{(1-r^2)^2 + (2(\zeta_e + \zeta_m)r)^2}},$$

that is

$$P_e = \frac{m\zeta_e \left(\frac{\omega}{\omega_n}\right)^3 \omega^3 Y_0^{\ 2}}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2(\zeta_e + \zeta_m)\frac{\omega}{\omega_n}\right]^2}$$




At resonance, that is $\omega=\omega_n$ , the maximum power is given by

$$P_e = \frac{m\zeta_e \omega_n^3 Y_0^{\ 2}}{4(\zeta_e + \zeta_m)^2} = \frac{m^2 d_e \omega_n^4 Y^2}{2(d_e + d_m)^2}$$

or with acceleration amplitude $A_0=\omega_n^2 Y_0$.

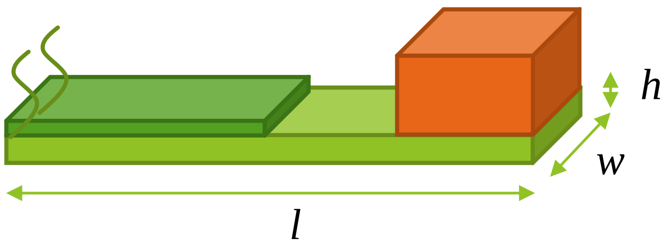
for a particular transduction mechanism forced at natural frequency $\omega_n$, the power can be maximized from the equation

$$P_{el} = \frac{m\zeta_e A^2}{4\omega_n(\zeta_m + \zeta_e)^2}$$

Max power when the condition $\zeta_e=\zeta_m$ is verified

# Microscale kinetic harvesters: scaling issues

PIEZOELECTRIC CANTILEVER




$$\omega_n = 2\pi C_n \sqrt{\frac{E}{\rho}} \frac{h}{l^2}$$

| Boudary conditions | C1 |
|---|---|
| doubly clamped | 1,03 |
| cantilever | 0,162 |

$$k = \xi \frac{Ewh^3}{l^3}$$

| Boudary conditions | Uniform load xsi | Point load xsi |
|---|---|---|
| doubly clamped | 32 | 16 |
| cantilever | 0,67 | 0,25 |

$$m_{eff} = m_{beam} + 0.32 m_{tip} = lwh\rho_{si} + 0.32(l/4)^3 \rho_{si}$$

$$P_{el} = \frac{m\zeta_e A^2}{4\omega_n(\zeta_m + \zeta_e)^2} = \frac{\left(lwh\rho_{si} + 0.32(l/4)^3 \rho_{mo}\right)}{8\omega_n \zeta_m} A^2 = \frac{\left(lwh\rho_{si} + 0.32(l/4)^3 \rho_{mo}\right)}{16\pi C_n \sqrt{\frac{E}{\rho_{si}}} \frac{h}{l^2} \zeta_m} A^2$$

At max power condition $\zeta_e = \zeta_m$

By assuming

$$A = 1g$$
$$\zeta_m = 0.01$$
$$h = l/200$$
$$w = l/4$$

$$P_{el} = \frac{\rho_{si}/800 + 0.32 \cdot 64 \rho_{mo}}{\frac{16}{200} \pi C_n \sqrt{\frac{E}{\rho_{si}}} \zeta_m} A^2 l^4$$

# Microscale kinetic harvesters: scaling issues

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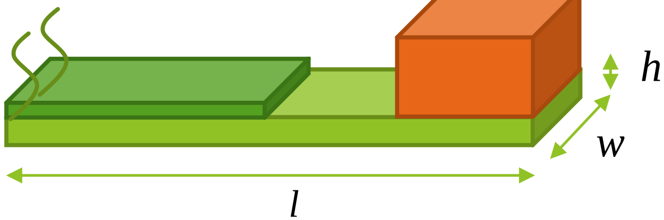


By assuming

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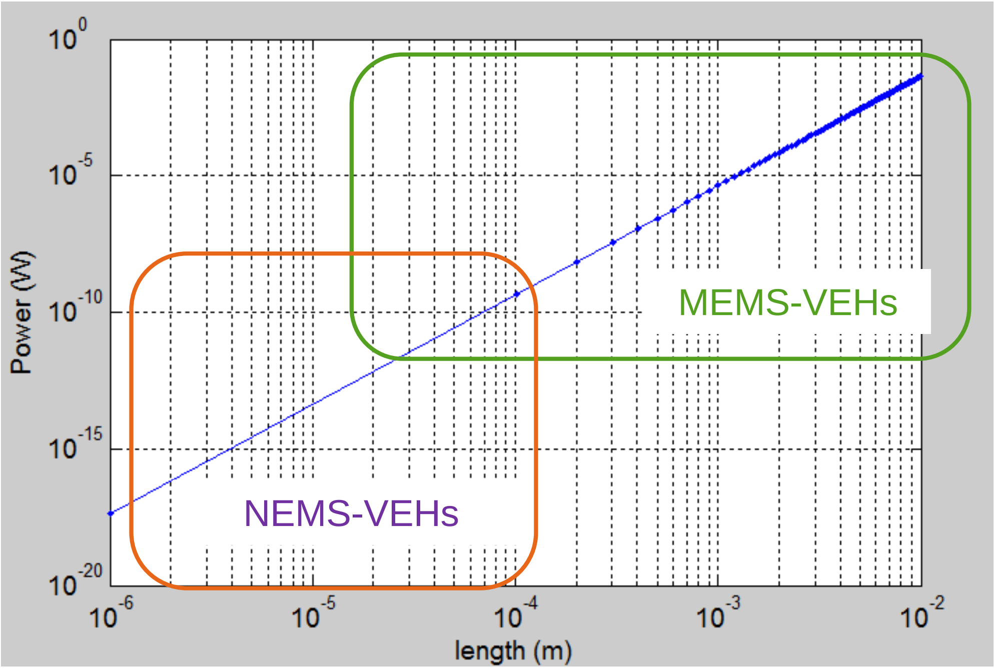
$$\zeta_m = 0.01$$

$$h = l / 200$$

$$w = l / 4$$



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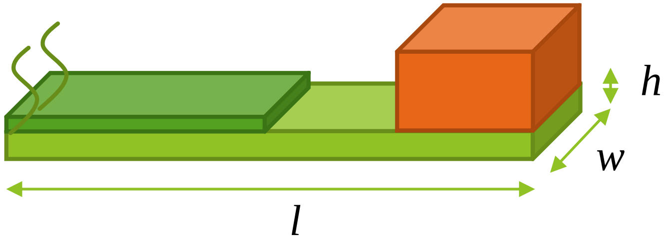


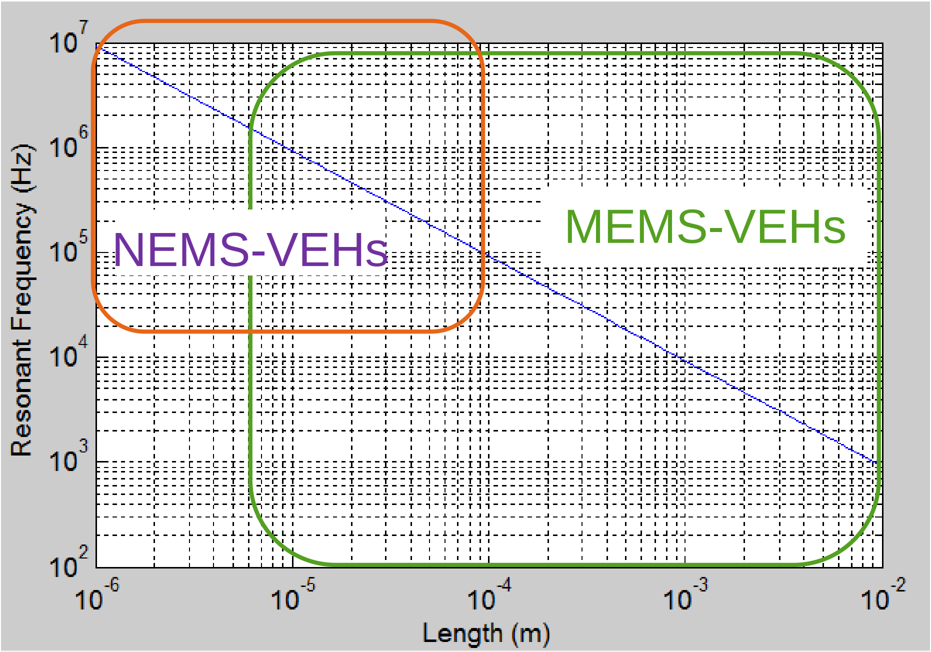

By assuming

$$A = 1g$$

$$\zeta_m = 0.01$$

$$h = l / 200$$

$$w = l / 4$$



# Microscale kinetic harvesters: scaling issues

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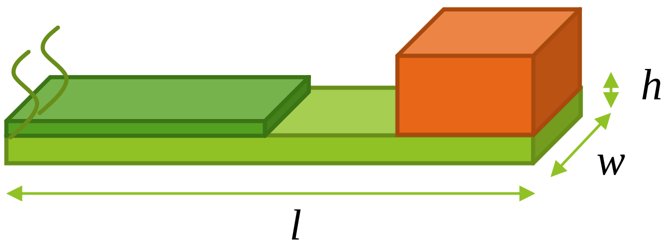
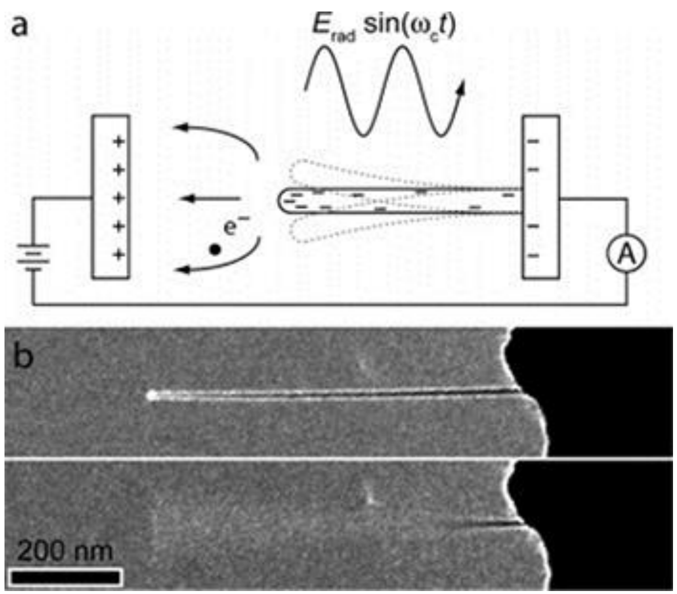
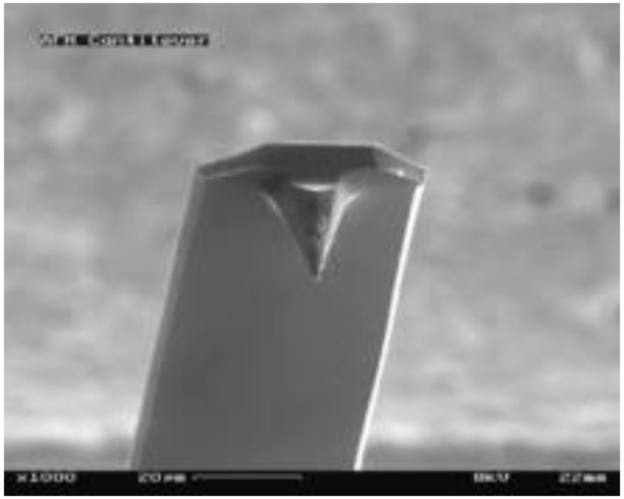



By assuming

$$A = 1g$$
$$\zeta_m = 0.01$$
$$h = l / 200$$
$$w = l / 4$$




Alex Zettl, California Univ. 2010



AFM cantilever

# Piezoelectric conversion

Strain-charge

$$\mathbf{S} = \mathbf{s_E} \cdot \mathbf{T} + \mathbf{d}^t \cdot \mathbf{E}$$

$$\mathbf{D} = \mathbf{d} \cdot \mathbf{T} + \boldsymbol{\varepsilon}_\mathbf{T} \cdot \mathbf{E}$$

Stress-charge

$$\mathbf{T} = \mathbf{c_E} \cdot \mathbf{S} - \mathbf{e}^t \cdot \mathbf{E}$$

$$\mathbf{D} = \mathbf{e} \cdot \mathbf{S} + \boldsymbol{\varepsilon}_\mathbf{S} \cdot \mathbf{E}$$

| Characteristic | PZT-5H | BaTiO3 | PVDF | AlN (thin film) |
|---|---|---|---|---|
| $d_{33}$ ($10^{-10}$ C/N) | 593 | 149 | -33 | 5,1 |
| $d_{31}$ ($10^{-10}$ C/N) | -274 | 78 | 23 | -3,41 |
| $k_{33}$ | 0,75 | 0,48 | 0,15 | 0,3 |
| $k_{31}$ | 0,39 | 0,21 | 0,12 | 0,23 |
| $\varepsilon_r$ | 3400 | 1700 | 12 | 10,5 |

$$k_{31}^2 = \frac{El.energy}{Mech.energy} = \frac{d_{31}^2}{s_{11}^E \varepsilon_{33}^T}$$

Electromechanical Coupling is an adimensional factor that provides the effectiveness of a piezoelectric material. IT's defined as the ratio between the mechanical energy converted and the electric energy input or the electric energy converted per mechanical energy input

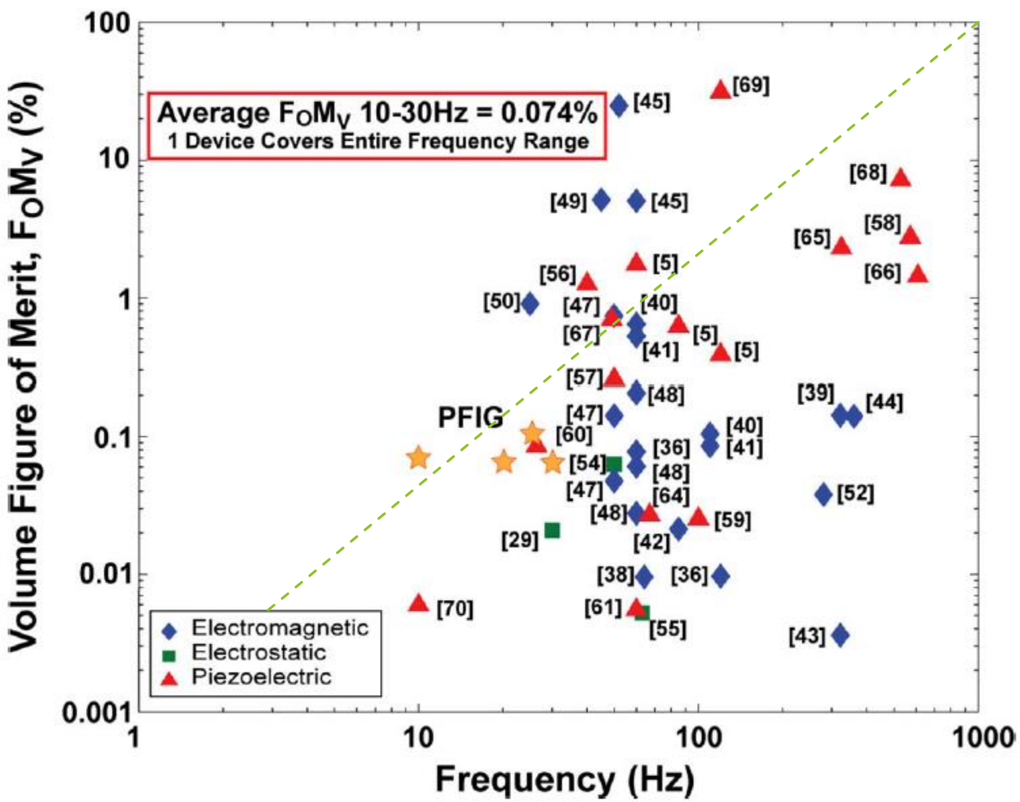
# Microscale kinetic harvesters: scaling issues

$$\mathrm{FoM_V} = \frac{\text{Useful Power Output}}{\frac{1}{16} Y_0 \rho_{Au} Vol^{\frac{4}{3}} \omega^3}$$

Bandwidth figure of merit

$$\mathrm{FoM_{BW}} = \mathrm{FoM_V} \times \frac{\delta\omega_{1\ \mathrm{dB}}}{\omega}$$

Frequency range within which the output power is less than 1 dB below its maximum value




Galchev et al. (2011)

Mitcheson, P. D., E. M. Yeatman, et al. (2008).

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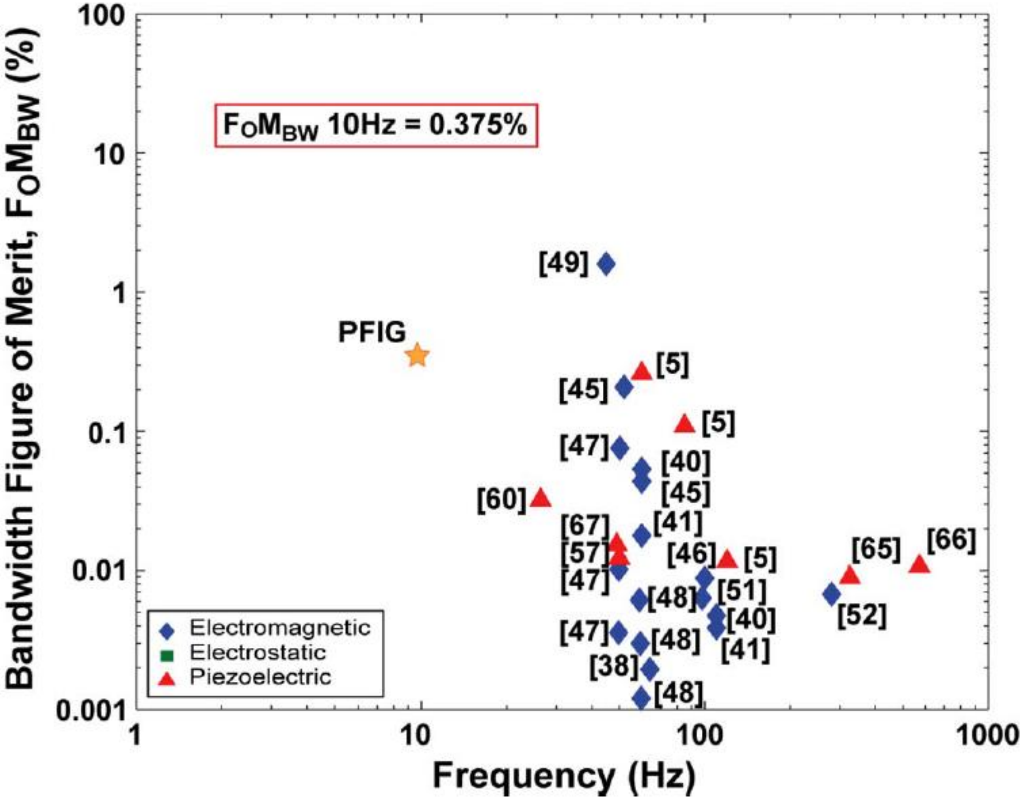


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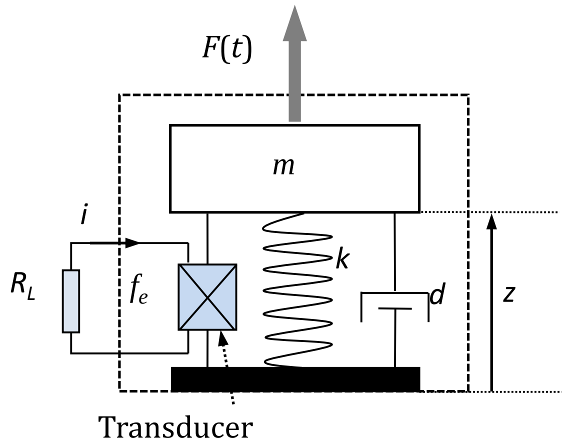
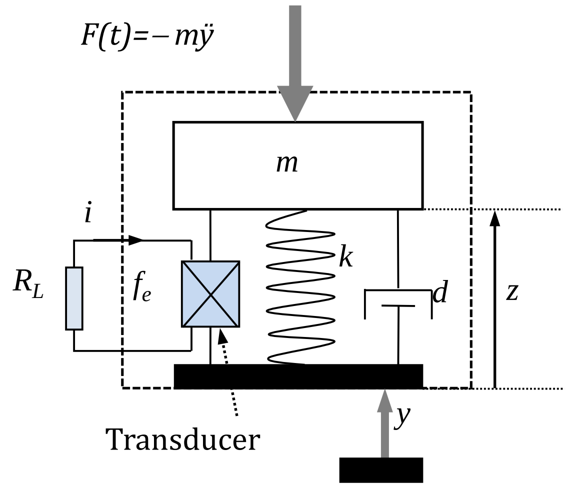
# Microscale kinetic harvesters: scaling issues



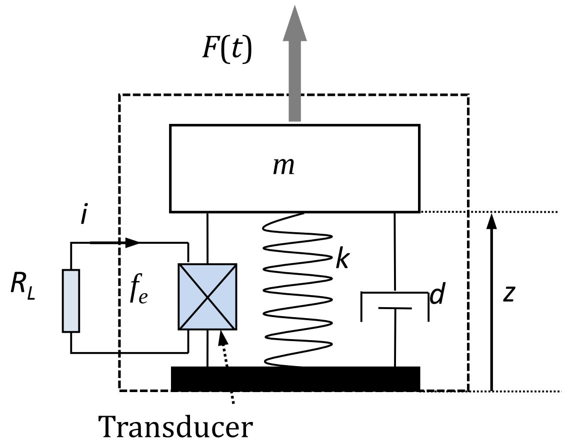



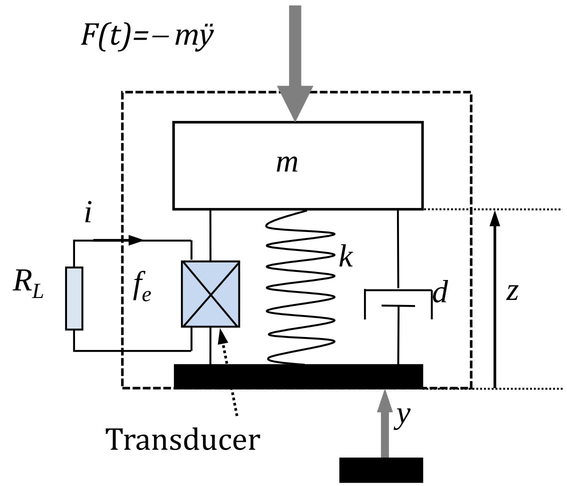

At micro/nano scale direct force generators are much more efficient because not limited by the inertial mass!!!

$$\begin{cases} m\ddot{z} + d\dot{z} + \dfrac{dU(z)}{dz} + \alpha V_L = F(t) \\ \dot{V}_L + (\omega_c + \omega_i)V_L = \lambda\omega_c\dot{z} \end{cases}$$

$$\begin{cases} m\ddot{z} + d\dot{z} + \dfrac{dU(z)}{dz} + \alpha V_L = -m\ddot{y} \\ \dot{V}_L + (\omega_c + \omega_i)V_L = \lambda\omega_c\dot{z} \end{cases}$$

# Microscale kinetic harvesters: scaling issues



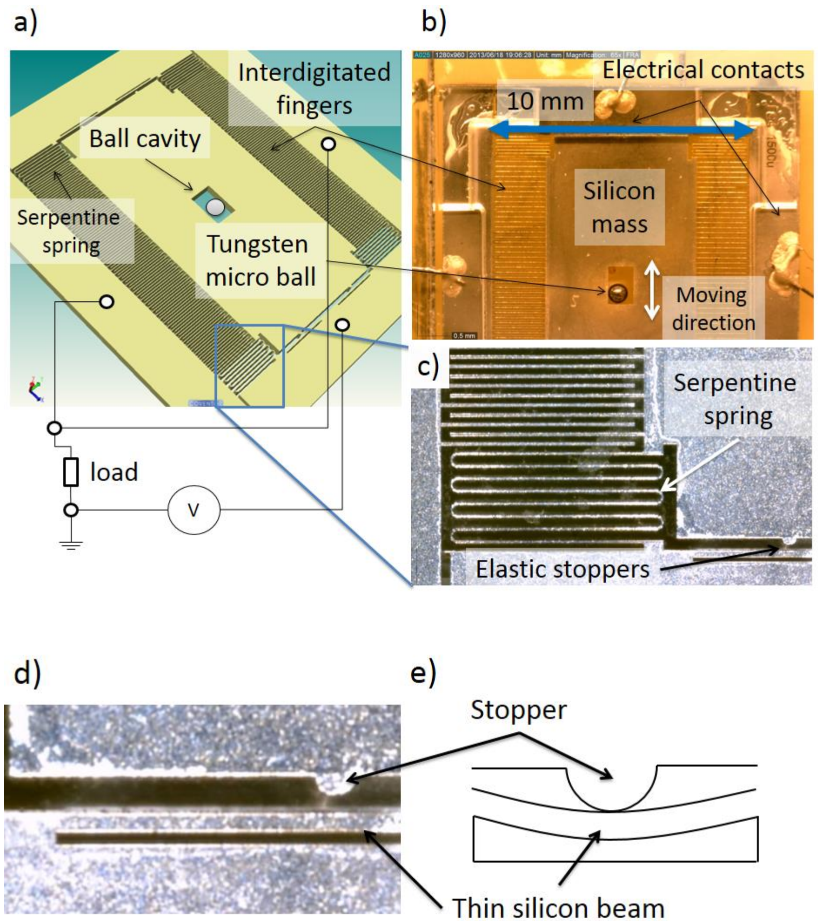

Power fluxes

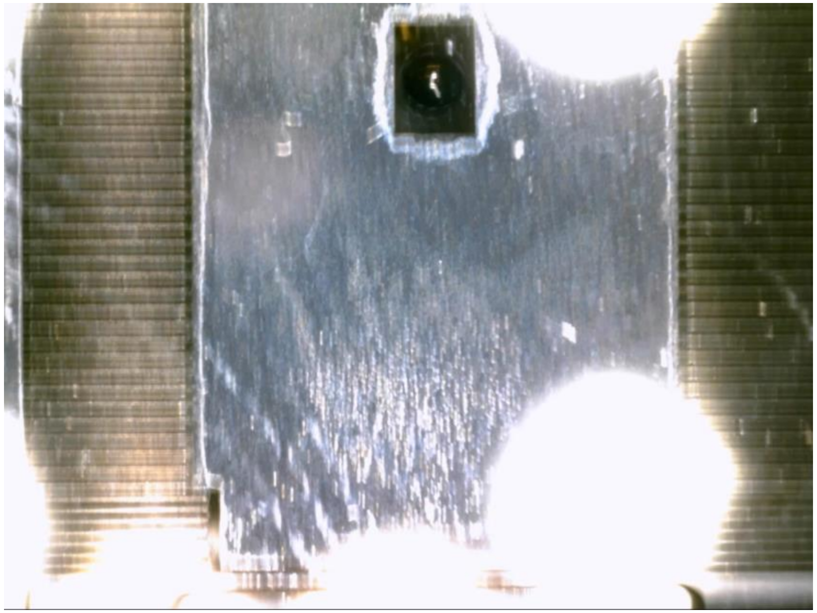
$$m\ddot{z}\dot{z} + d\dot{z}^2 + \frac{dU(z)}{dz}\dot{z} + \alpha V_L \dot{z} = F(t)\dot{z}$$

$$P_m(t) = F(t)\cdot\dot{z}(t)$$

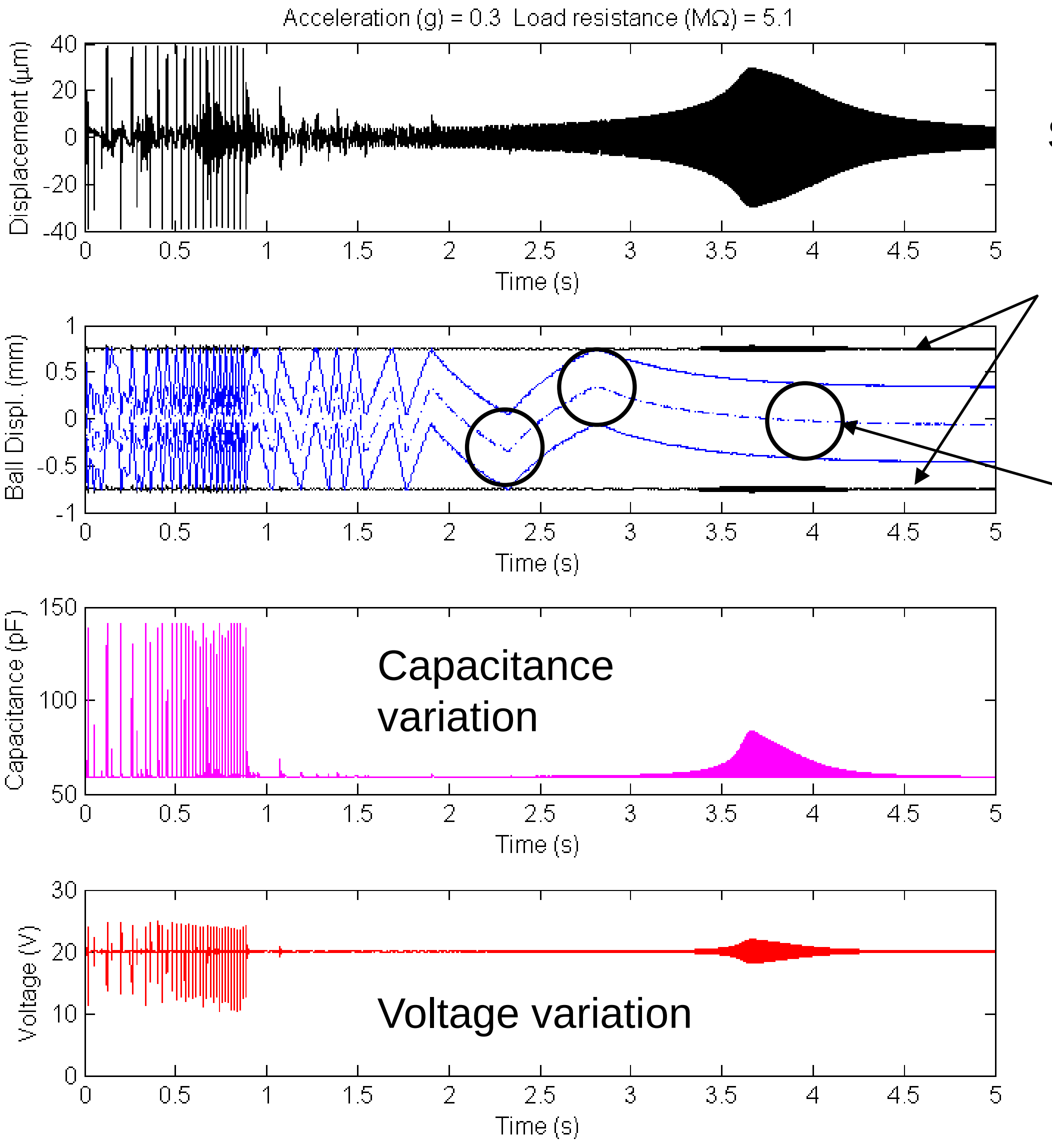
$$P_m(t) = -m\ddot{y}\cdot\dot{z} = -\rho l^3 \cdot \dot{z}$$

# Nonlinear MEMS electrostatic kinetic energy harvester



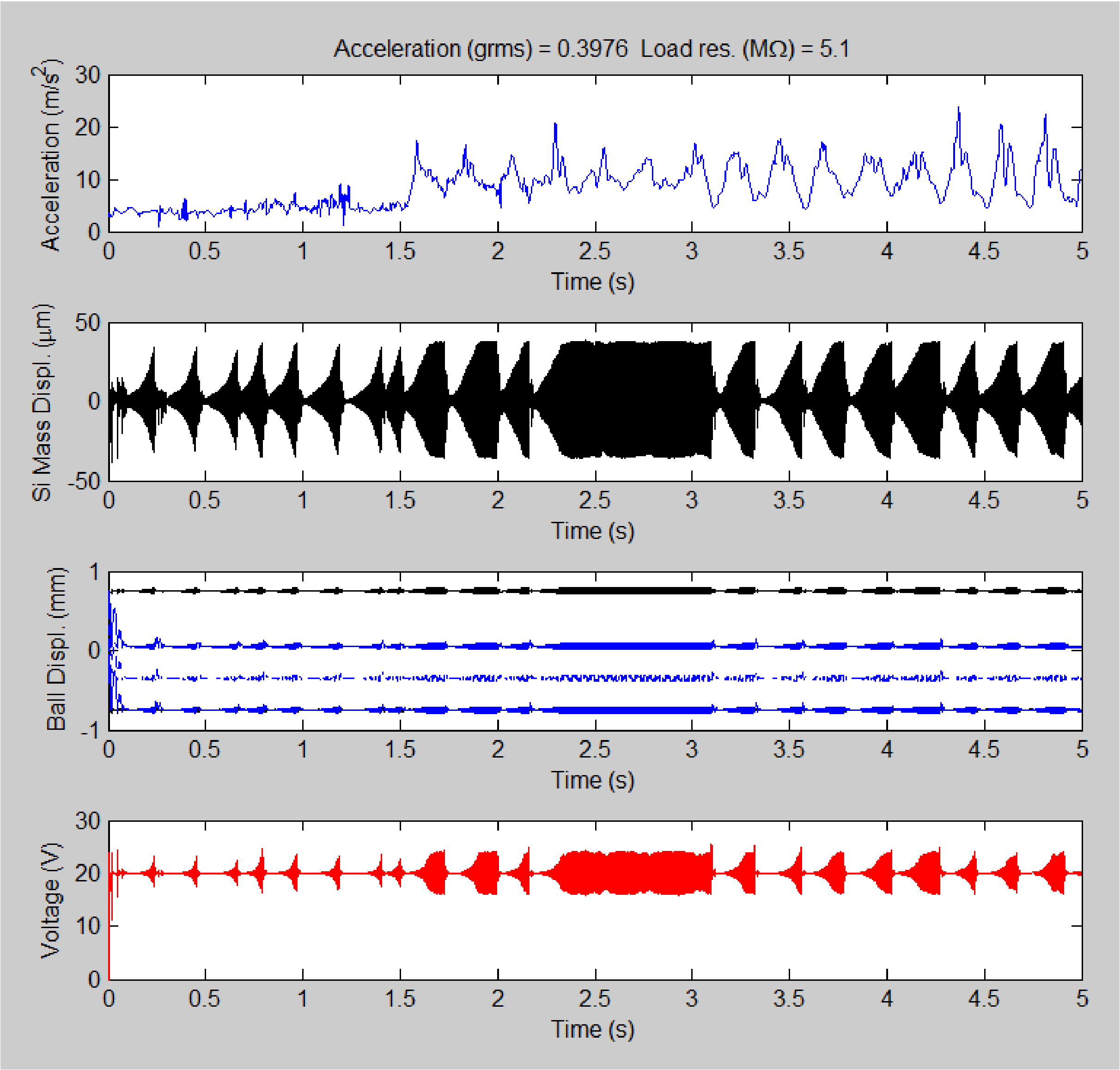
# Electrostatic generators




Sine sweeping from 1 to 200 Hz within 5 seconds of time.

**At low frequency the ball transfer its kinetic energy to the oscillating silicon mass throughout impacts with inner walls of the cavity. After the impact the mass resonate at its natural frequency (163 Hz) and this energy is converted by the coupling with electrostatic transducer.**

# Electrostatic generators



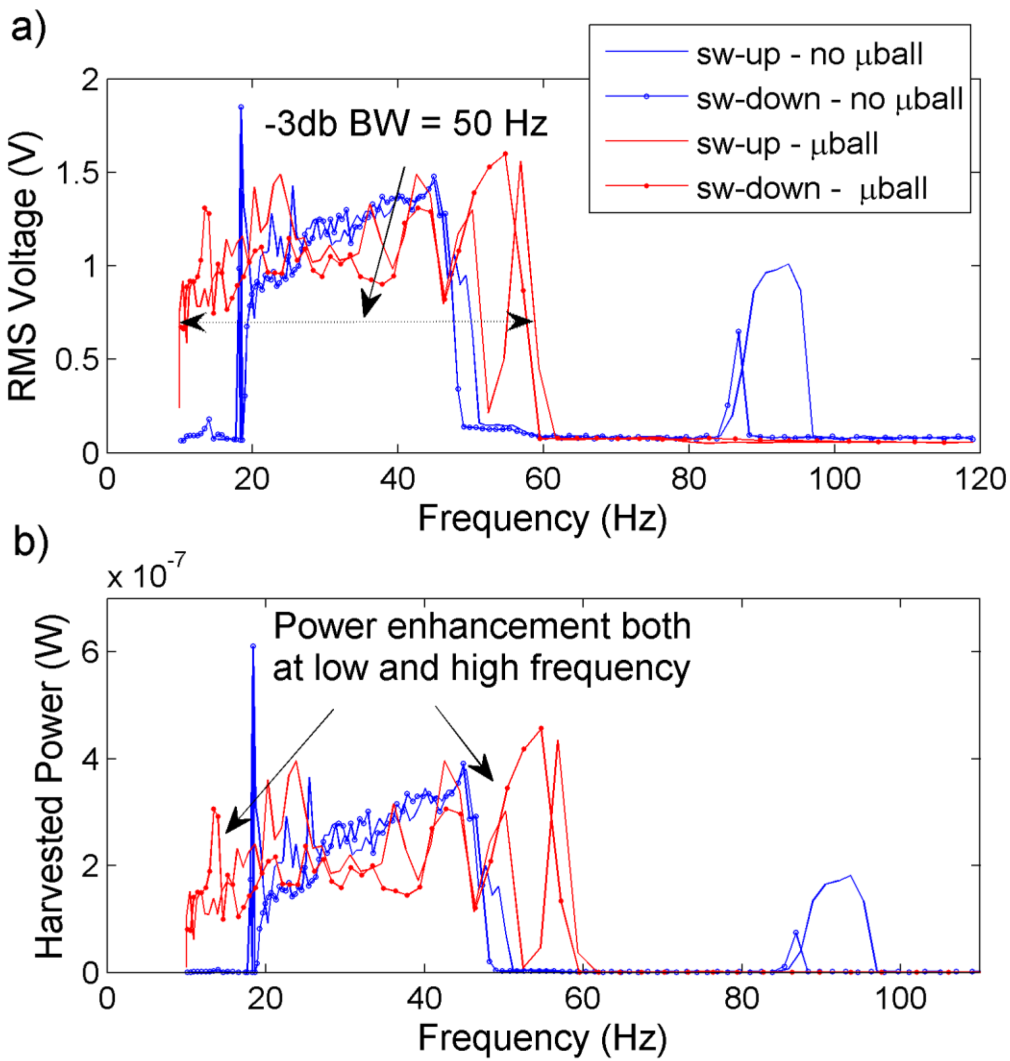

**INPUT SIGNAL**: walking man

RMS acceleration: 0.39 grms

Generated Power: 1.34 μW

Bias voltage: 20 V

MEMS direction: X




F. Cottone et al., *2014 IEEE 27th Int. Conf. Micro Electro Mech. Syst,* 2014.

# Conclusions

- Many potential applications are waiting for powerful MEMS/NEMS harvesting system to enable self-powering features
- Inertial vibration energy harvesters are very limited at small scale -> direct force piezoelectric/electrostatic devices are more efficient at nanoscale
- Design challenges
  - Materials with high electromechanical coupling,
  - Cheap miniaturization/fabrication processes
  - Very efficient conditioning electronics
- In general the specific application decides if one or many micro-VEH are the best choice with respect to one macro-scale VEH

# Thank you


United Kingdom
Isle of Man
Leeds
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Bristol
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Denmark
Copenhagen
Hamburg
Bremen
Berlin
Belgium
Cologne
Germany
Luxembourg
Prague
Czech Republic
Paris
Vienna
Munich
Austria
Zurich
Switzerland
France
Lyon
Geneva
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Croatia
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ESIEE
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