Electrostatic Vibration Energy Harvesting Microsystems for Self-Powered Minimally Invasive Pacemakers

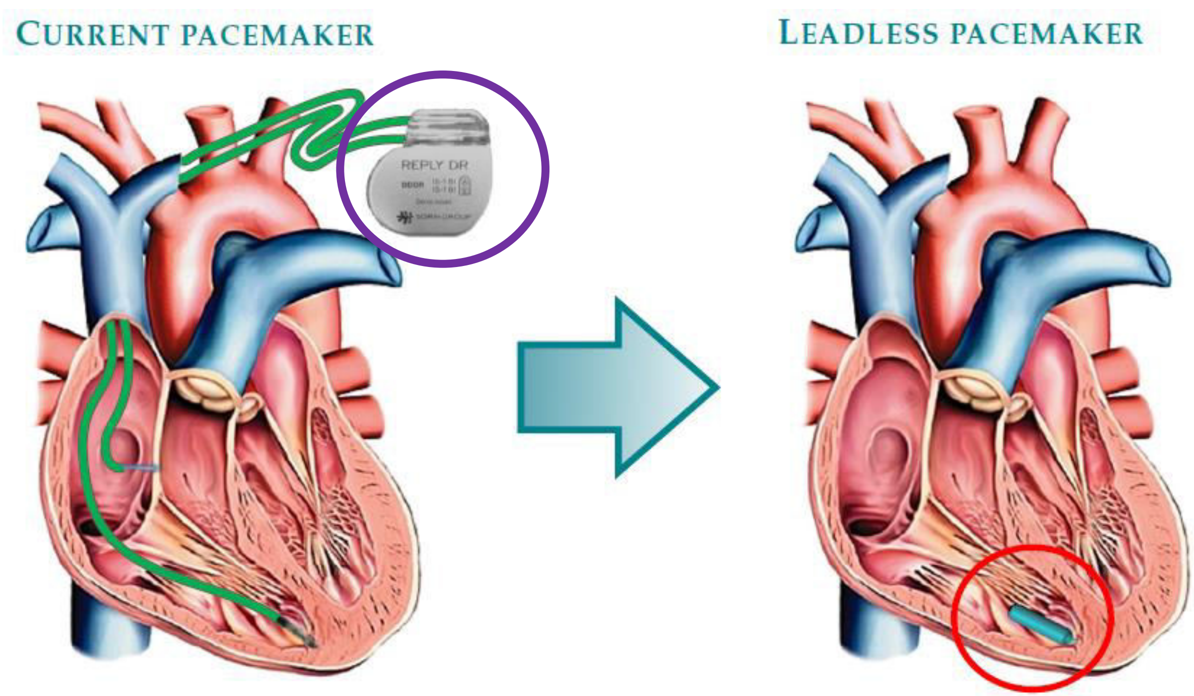
E. Lefeuvre, S. Risquez, J. Wei, B. Vysotskyi,

P. Gaucher, D. Aubry, F. Parrain, M. Woytasik, H. Mathias and F. Costa

OUTLINE

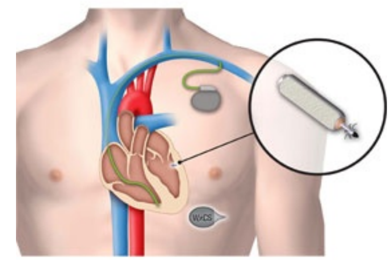
1. Leadless Pacemakers
2. 3D Electrostatic Energy Harvester
3. Frequency-up Energy Harvester
4. Interface Circuits

Leadless Pacemakers



Volume ~ 8 cm^3 → Volume < 1 cm^3

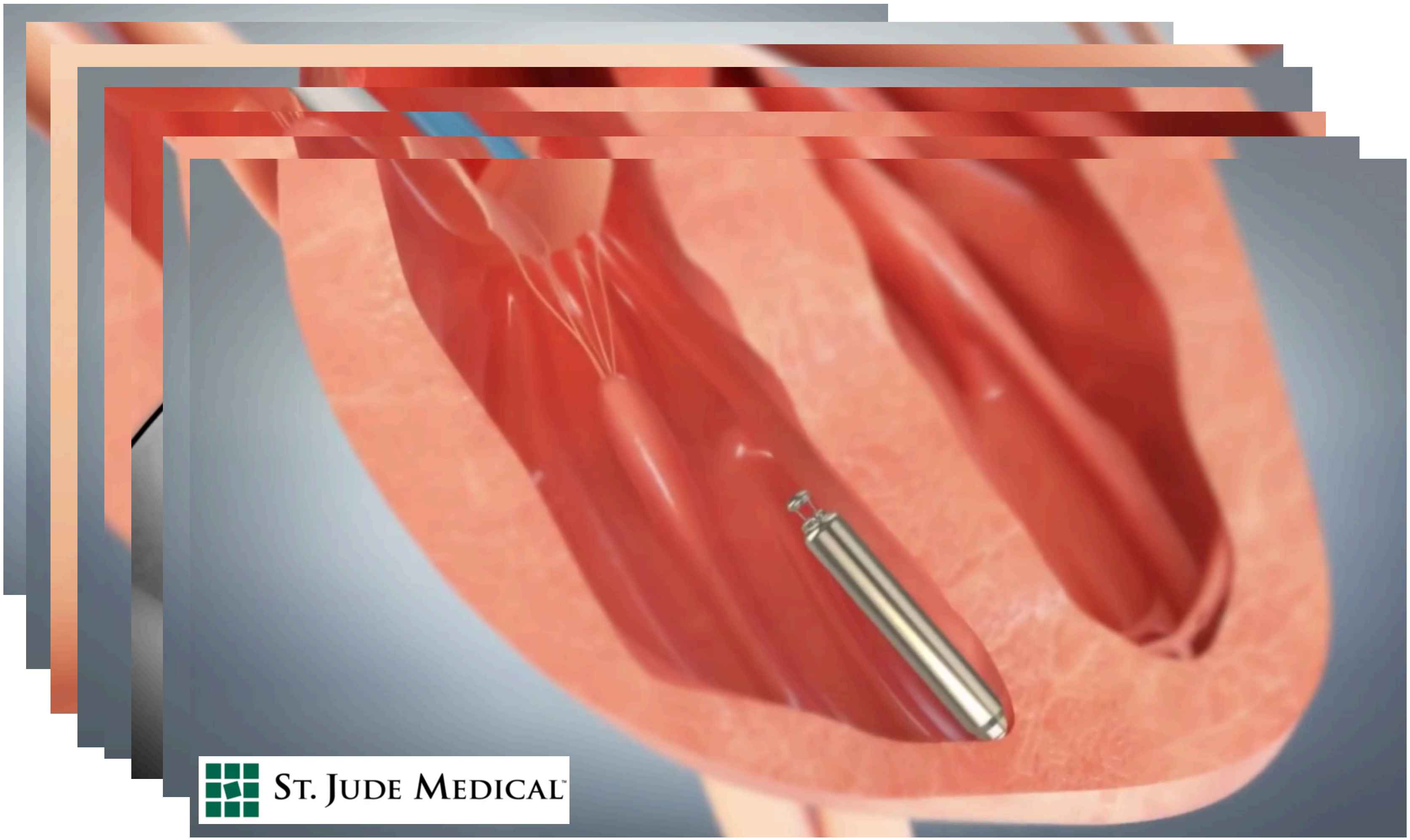
Medtronic (2011)
Battery – 7 years



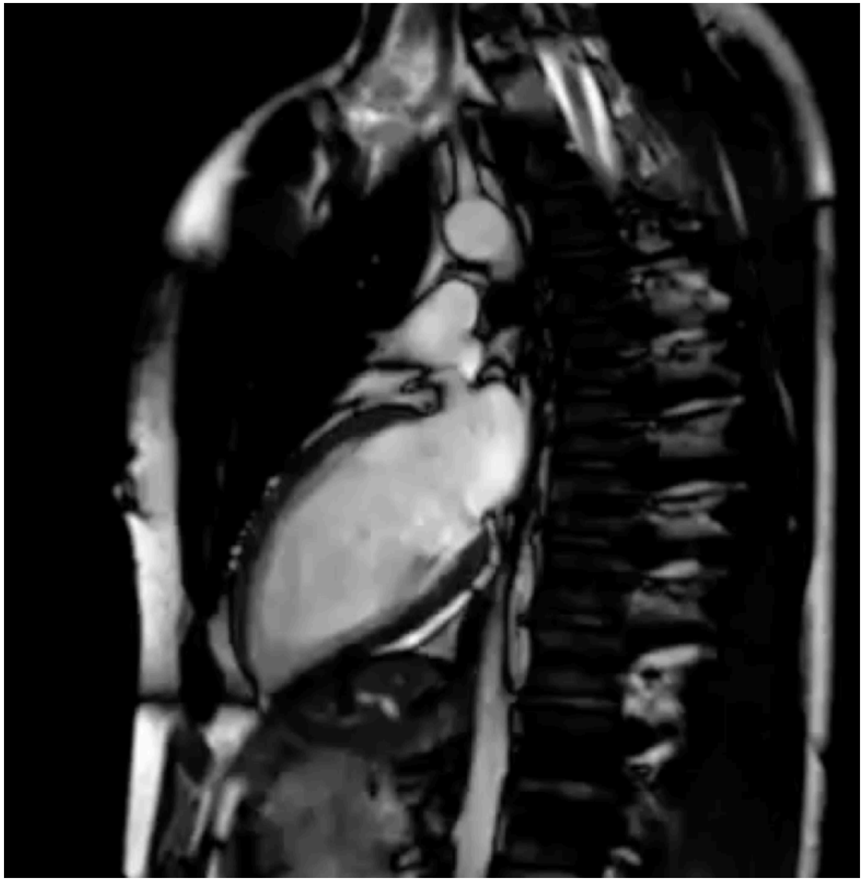
EBR (2010)
Ultrasound external source

Nanostim, St Jude (2011)
Battery – 7 years

Implantation Procedure



Mechanical Energy



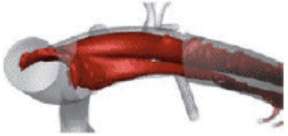
Chemical Energy

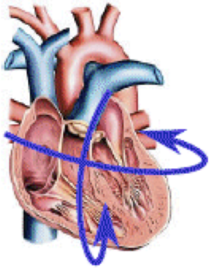
↓

Muscle contraction

↙ ↘

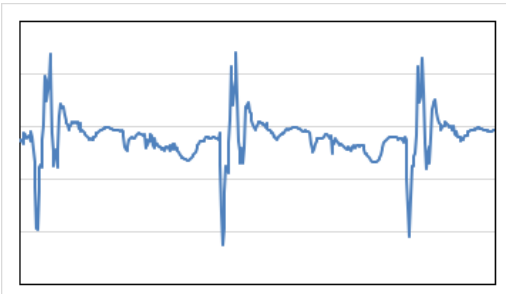
Blood Flow + Movement



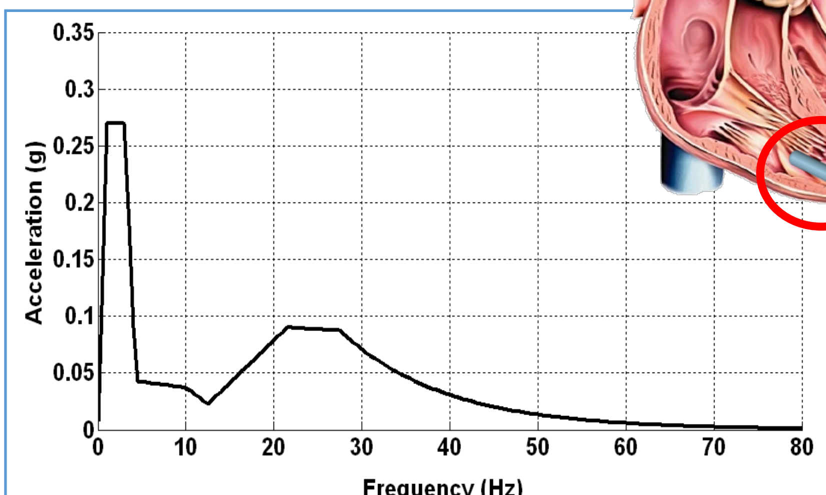


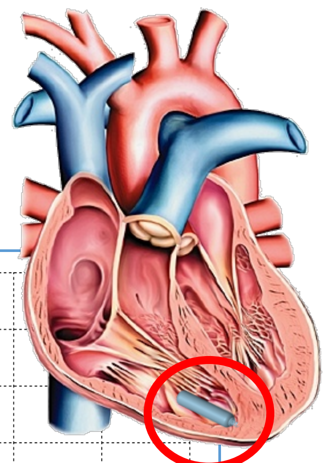
Available Mechanical Energy from Heart Wall Motion?

Acceleration vs. time



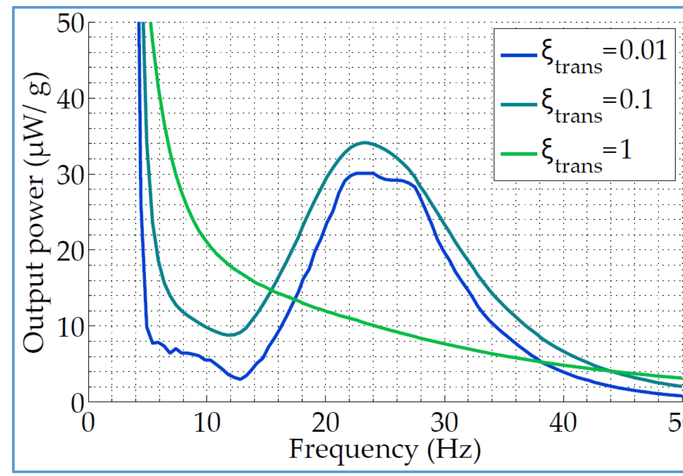
Acceleration vs. frequency





Deterre et al., 2011

Harvester Power vs. resonant frequency

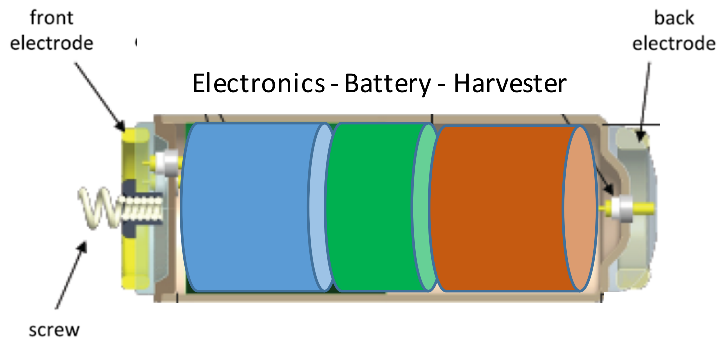


Estimated Mechanical Power:

~ 25 µW/gram [20 Hz – 30 Hz]

Energy Harvester Requirements:

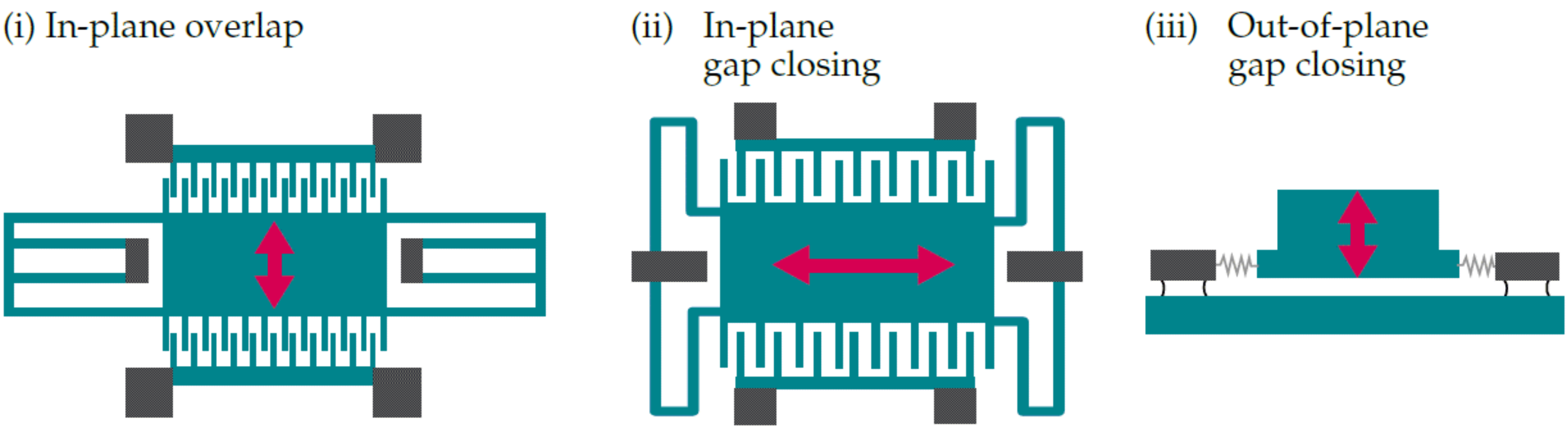
- No magnetic components → MRI compatibility
- Long term reliability → 20 years or more… and **+600 million** heartbeat
- Volume < 0.5 cm^3
- Power > 5µW
- Fit in a 6 mm-diameter capsule → Cathether implantation



Interest of Electrostatic Transduction:

- Energy conversion independant of the transducer mechanical stress
  → larger degrees of freedom (shape, resonant frequency, power)
- Well adapted to miniaturization

Electrostatic Energy Harvesting MEMS: mostly 2D



Planar structures:

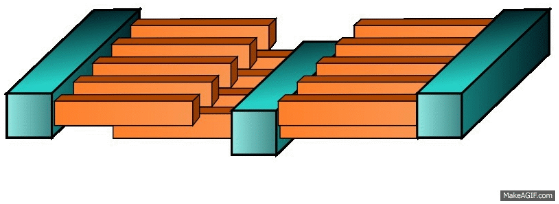
→ Adapted to cylindrical packaging of leadless pacemakers?

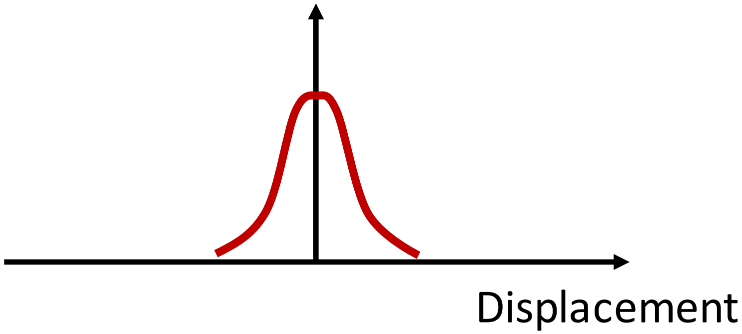
3D Energy Harvester

Proposed 3D MEMS: Vertical Comb Structure

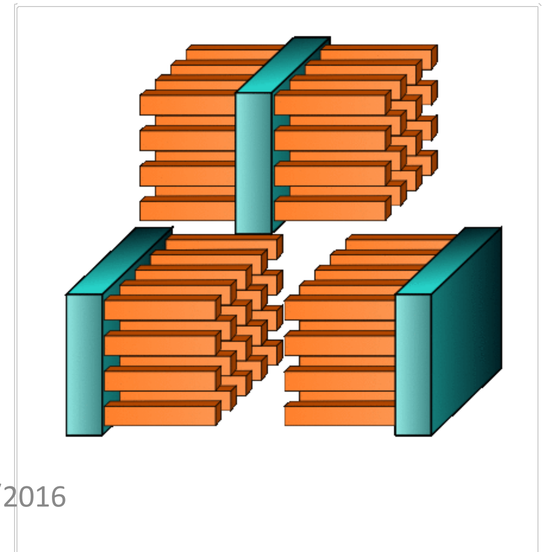
[Ms. Sarah Risquez Ph.D Work]

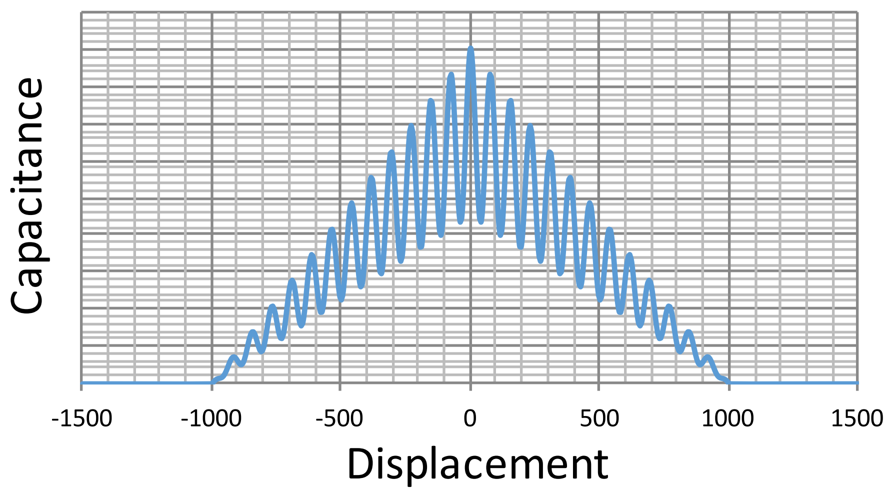
- One layer



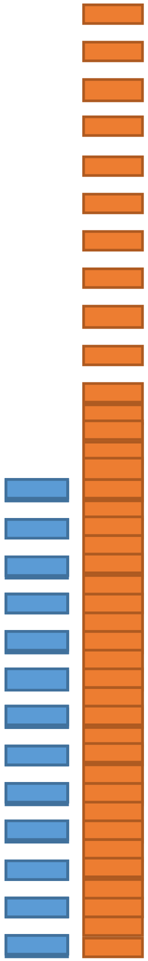


- Several layers

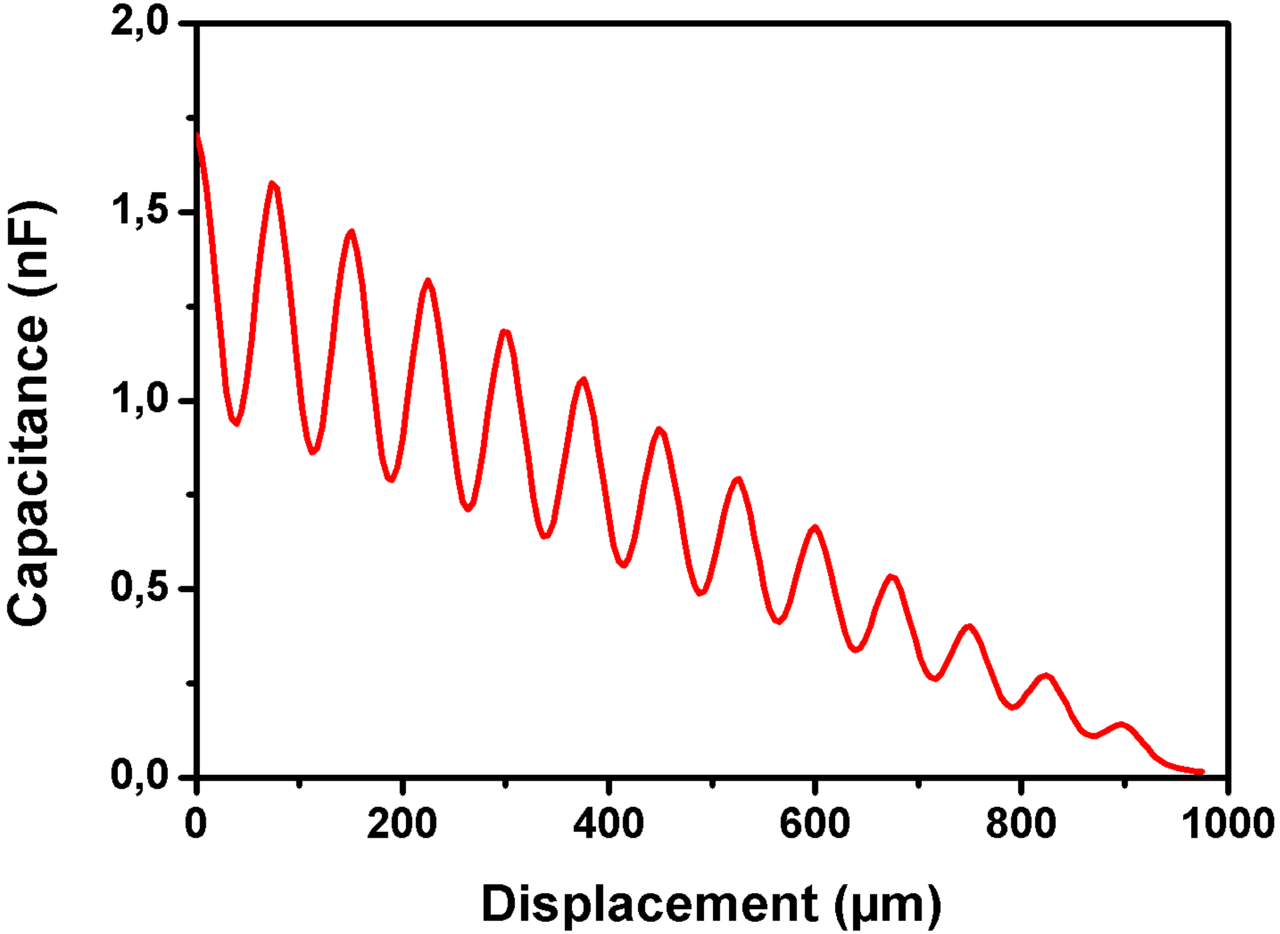




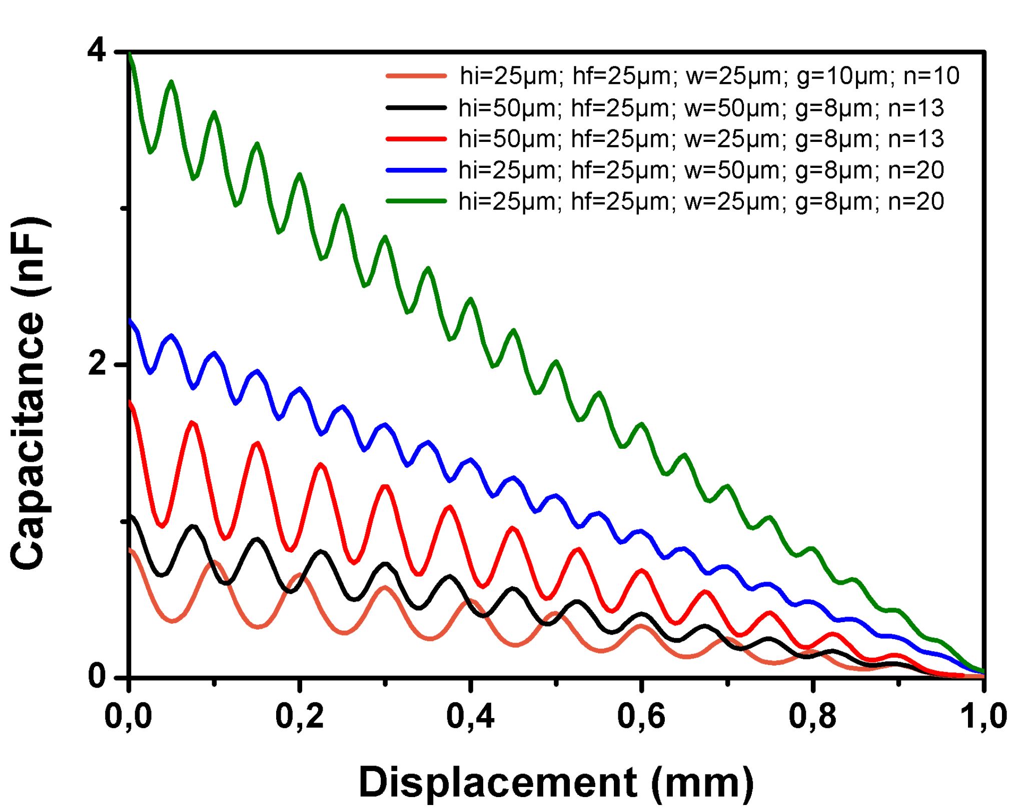
3D Energy Harvester

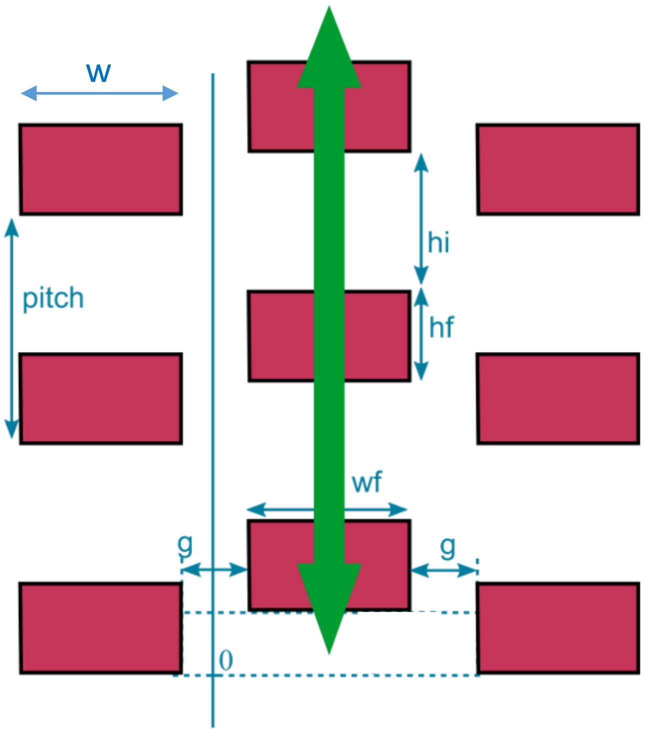


13 layers



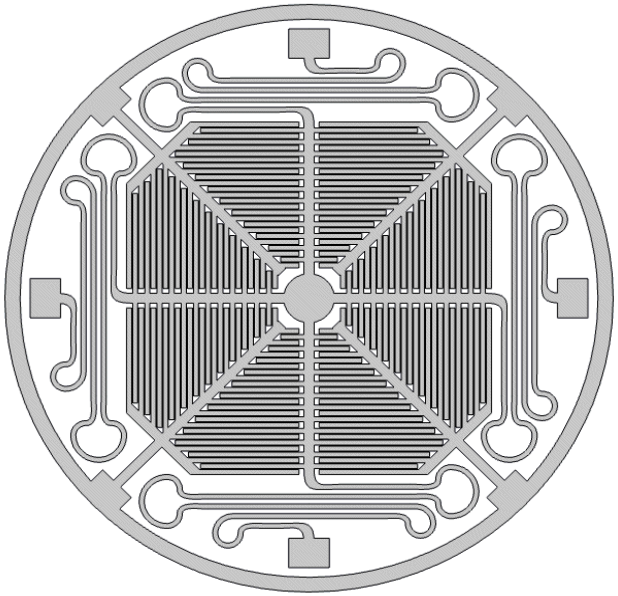
Design variables: w, hi, hf, g, number of layers



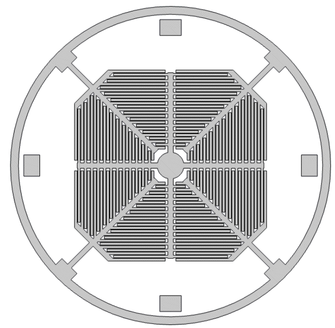


3D Energy Harvester

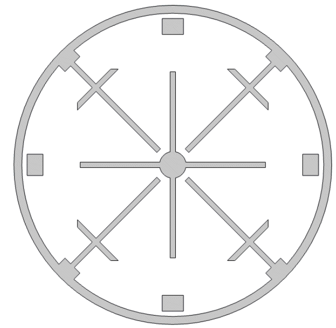
Design:



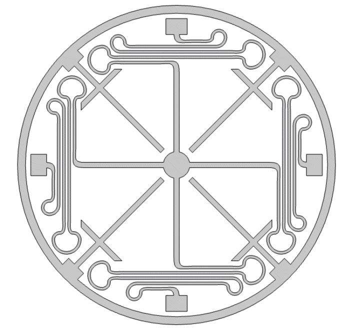
Top view



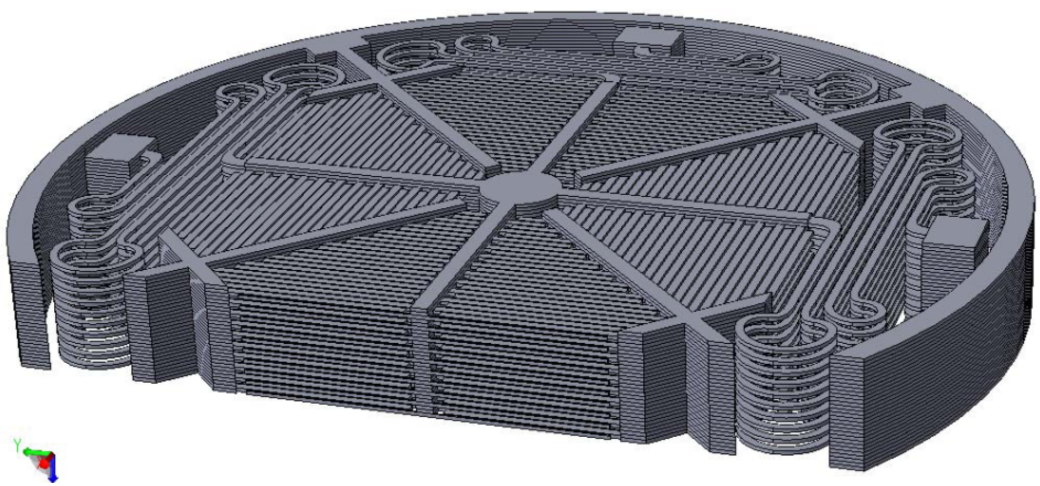
Comb layer



Inter-layer

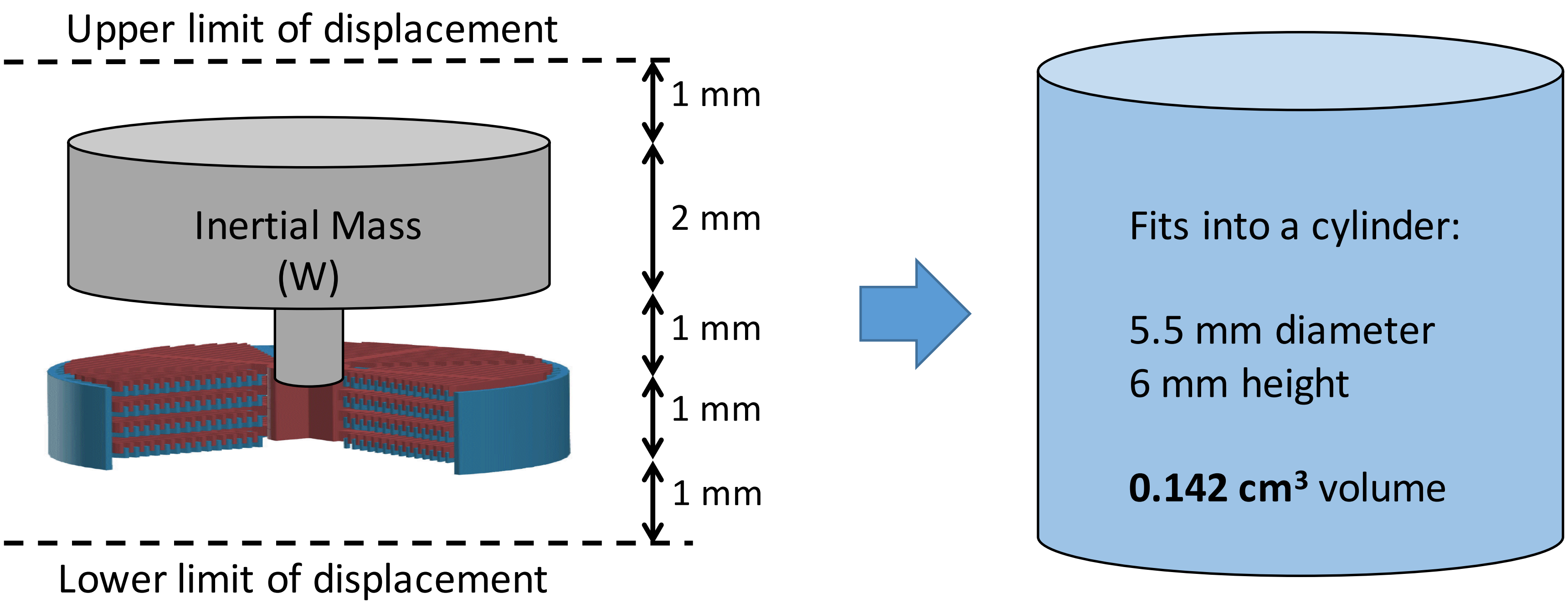


Spring layer



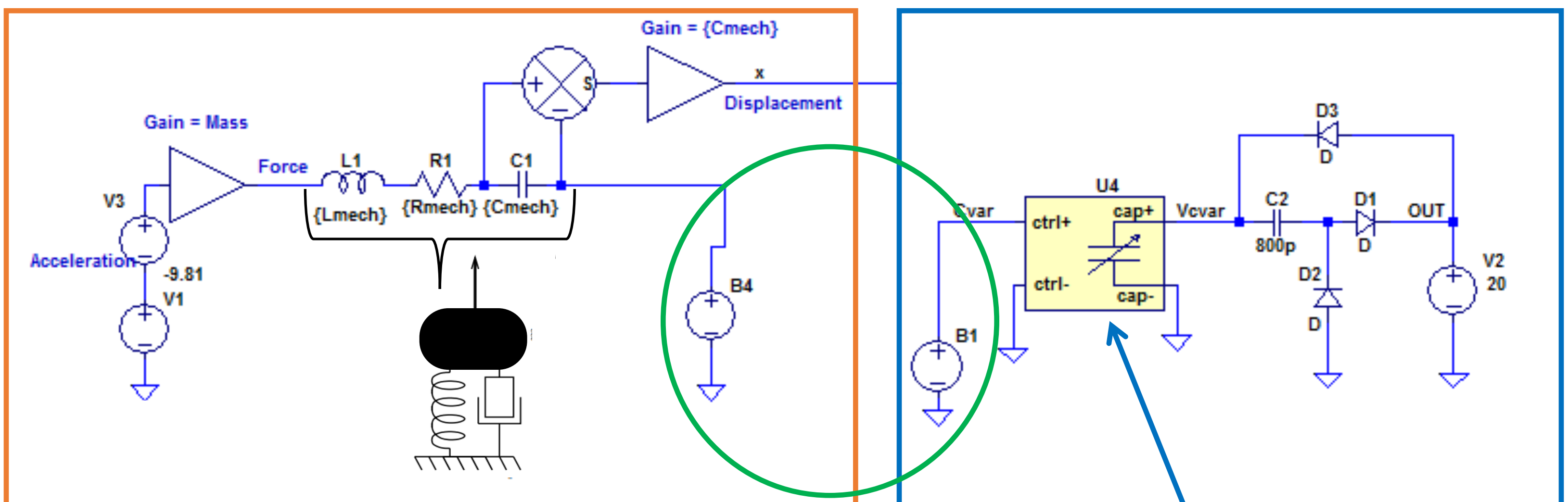
CAD view

Design:


Upper limit of displacement
1 mm
2 mm
1 mm
1 mm
1 mm
Inertial Mass
(W)
Lower limit of displacement
Fits into a cylinder:
5.5 mm diameter
6 mm height
0.142 cm^3 volume

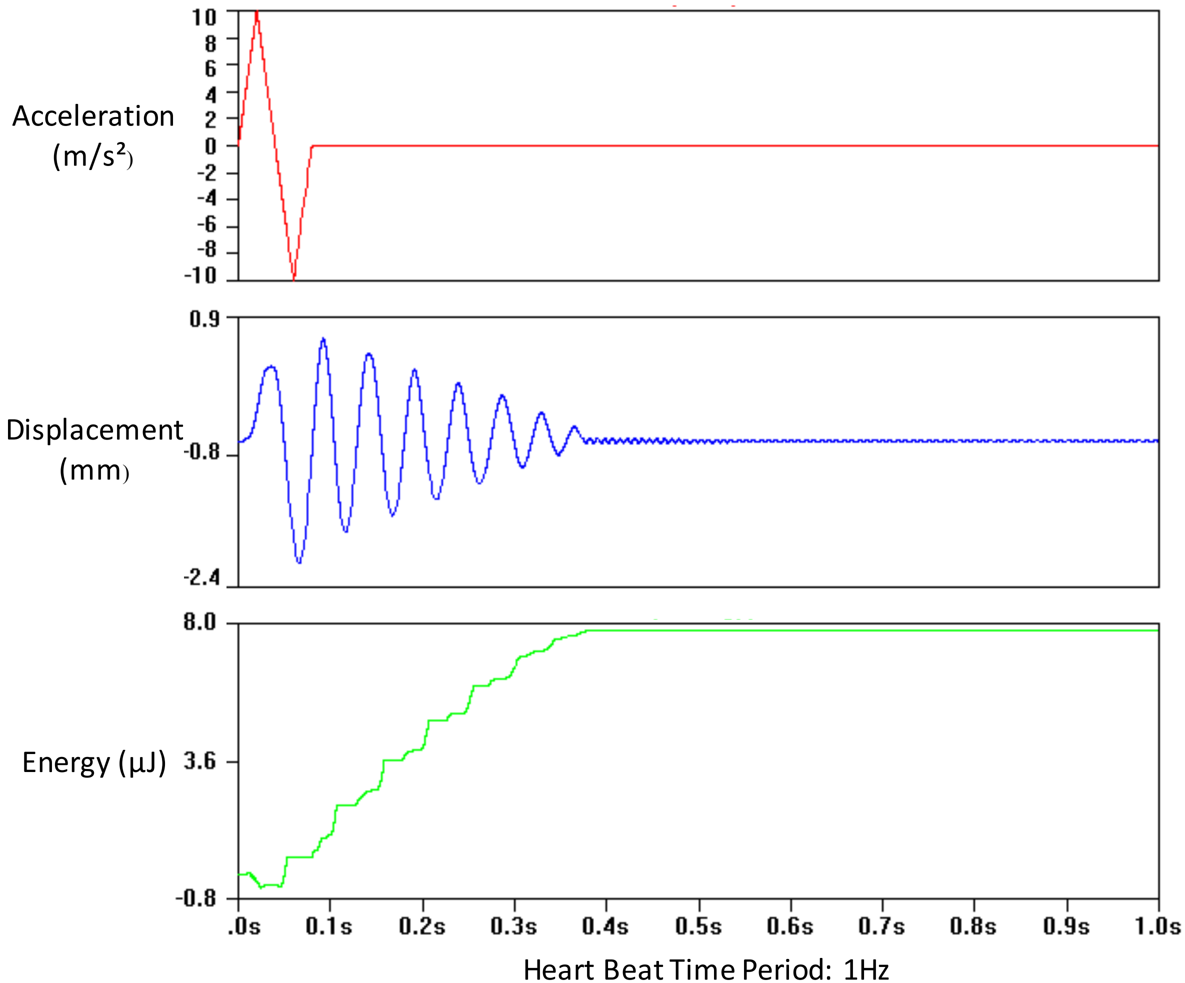
Behavioral Modelling (equivalent circuit representation):

Mechanical part **Electrical part**



Coupling **Electrostatic transducer**

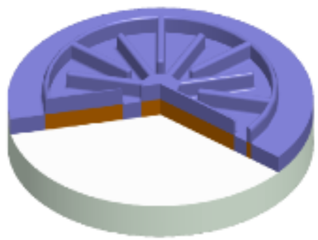
Behavioral Modelling (equivalent circuit representation):



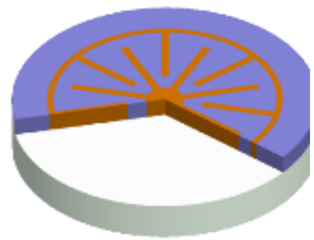
Resonant Frequency : **20 Hz**
Mechanical quality factor: **Q=30**
Average Electrical Power: **7.9 µW**

Microfabrication Process: electroplated nickel (structural) and copper (sactificial)

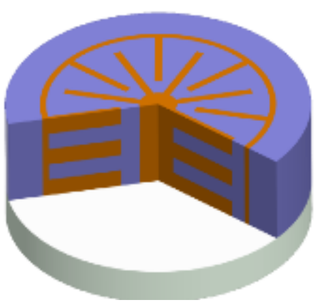
(i) Structural layer micromolding



(ii) Sacrificial layer uniform deposition



(iii) planarization



(iv) Multilayer stacking : repeat steps (i) → (iii)

(v) Final structure release

Copper sputtering

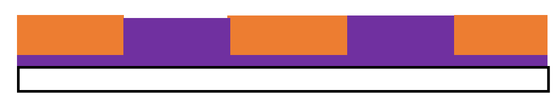
Photoresist Patterning

Nickel electroplating

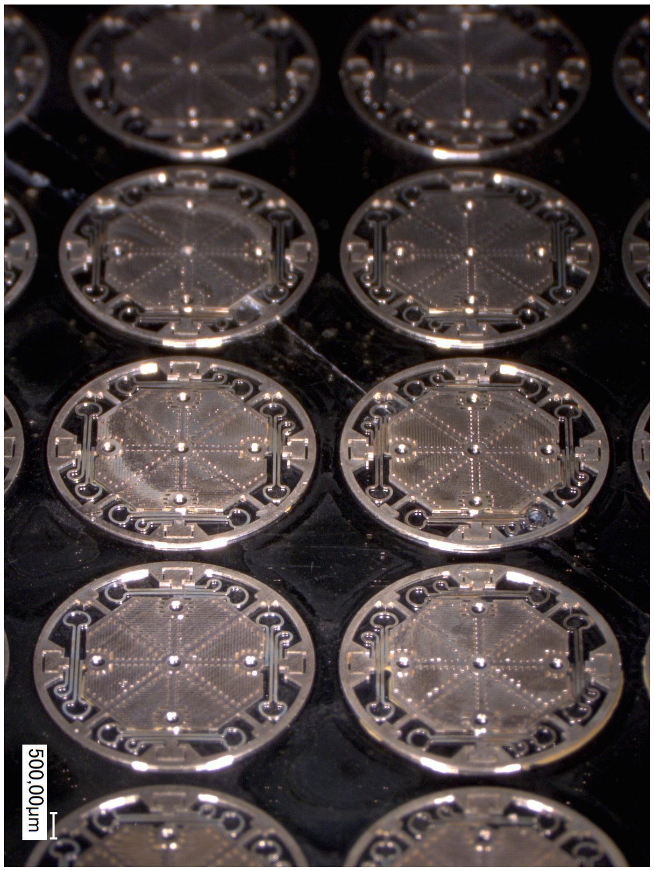
Photoresist Removal

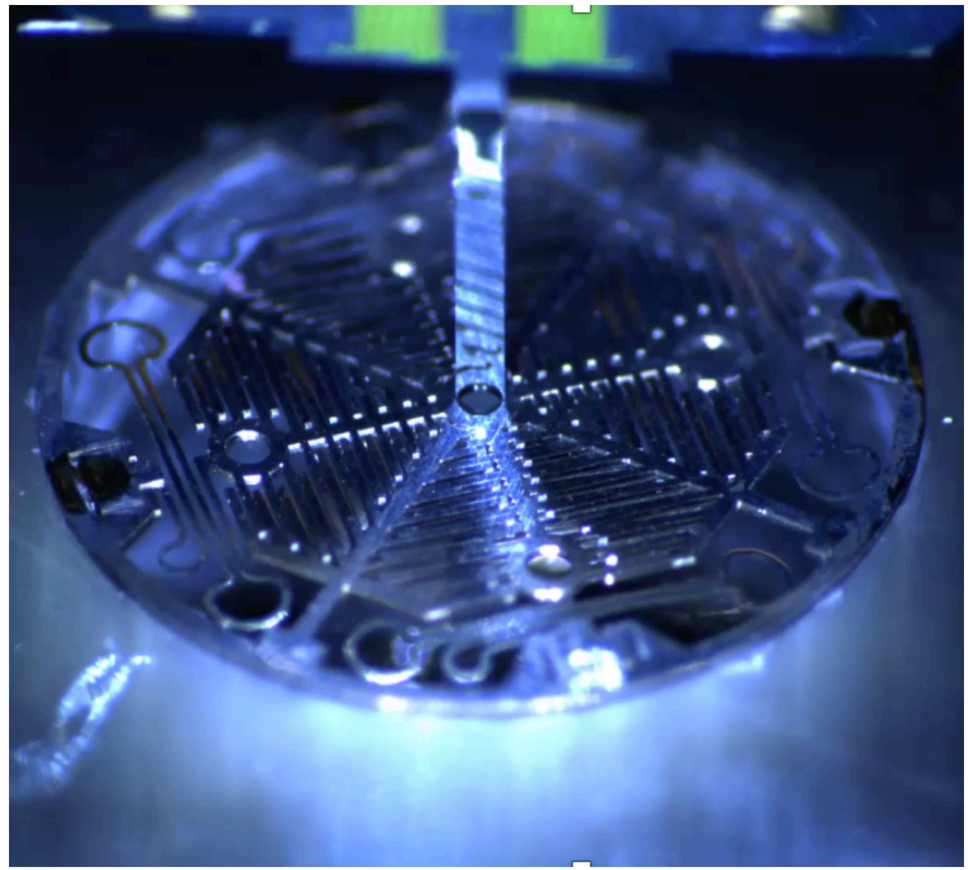
Copper electroplating

Planarization



First Prototypes:



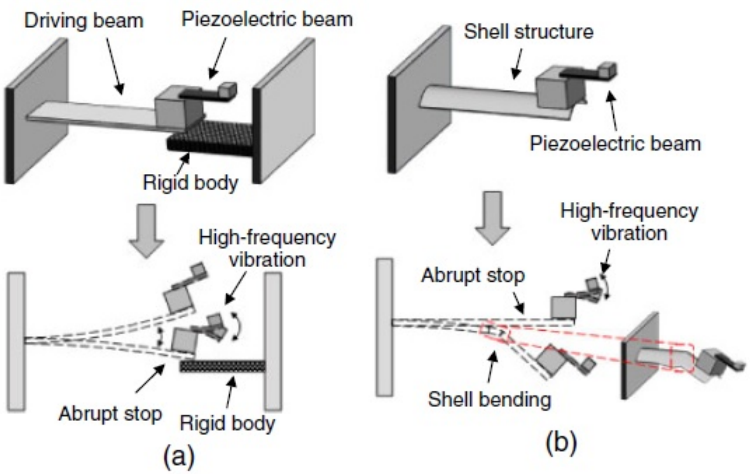


Frequency-up Energy Harvester

Frequency-up → Larger Bandwidth & Higher power density

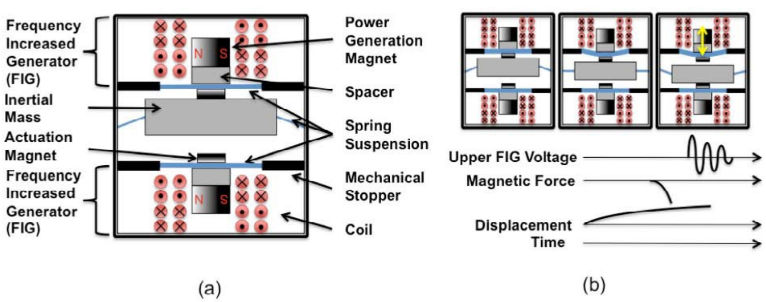
[Mr. Bogdan Vysotskyi Ph.D Work]

Piezo converter



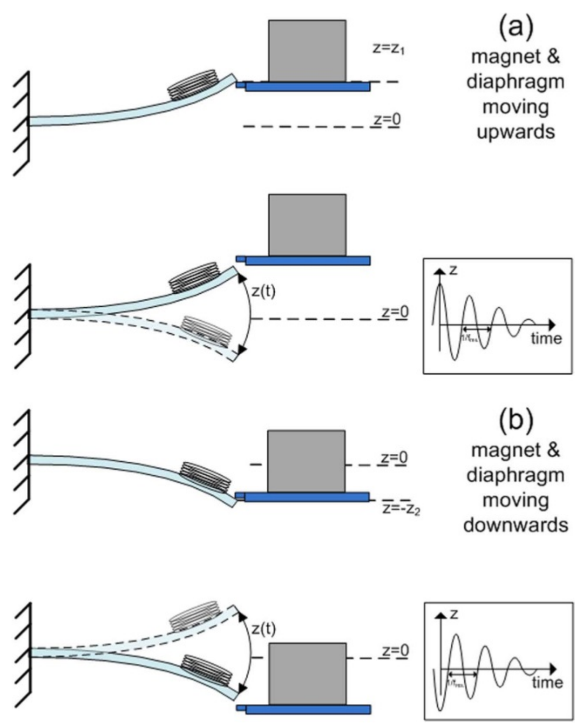
Jang, 2015

Magnetic converter



Galchev, 2009

Piezo-Magnetic converter

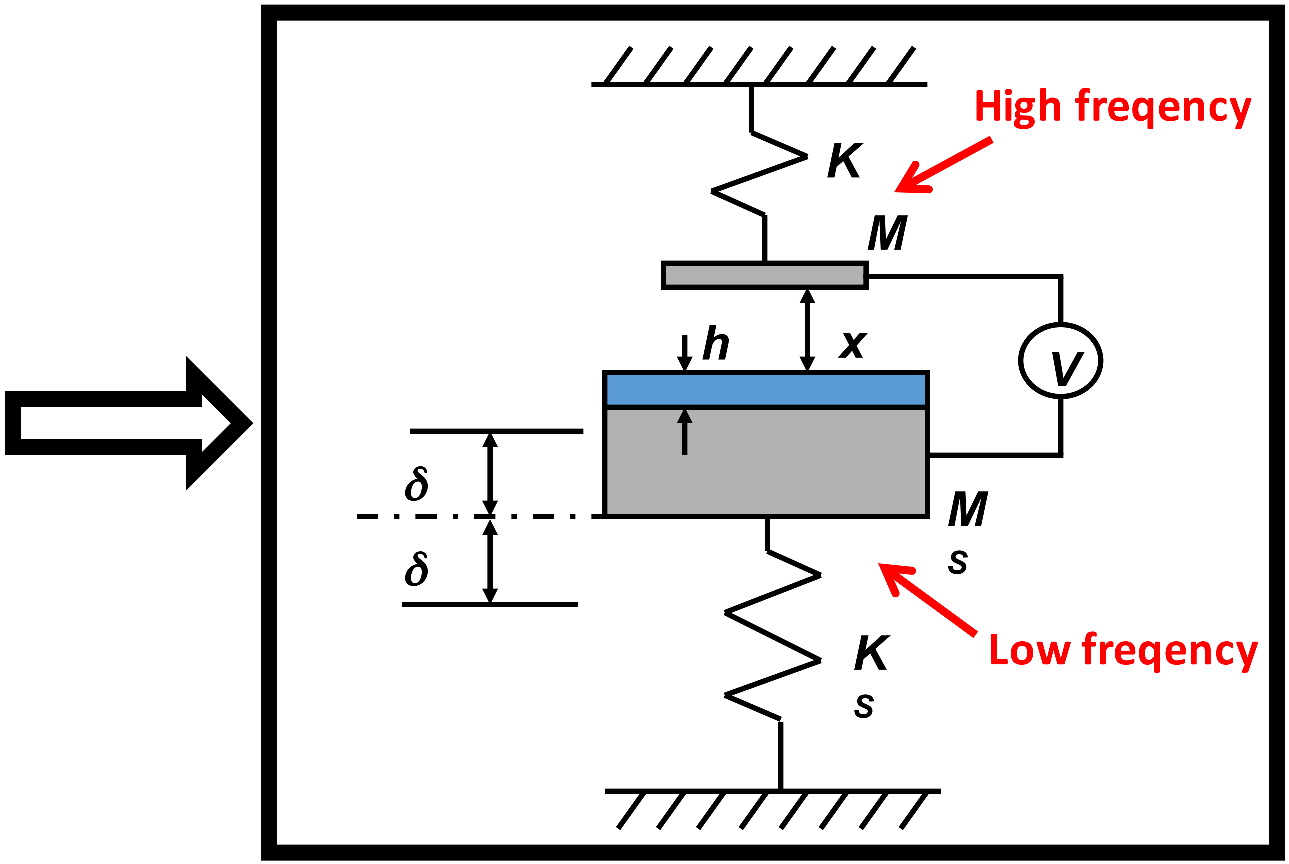


Zorlu, 2011

Frequency-up Energy Harvester

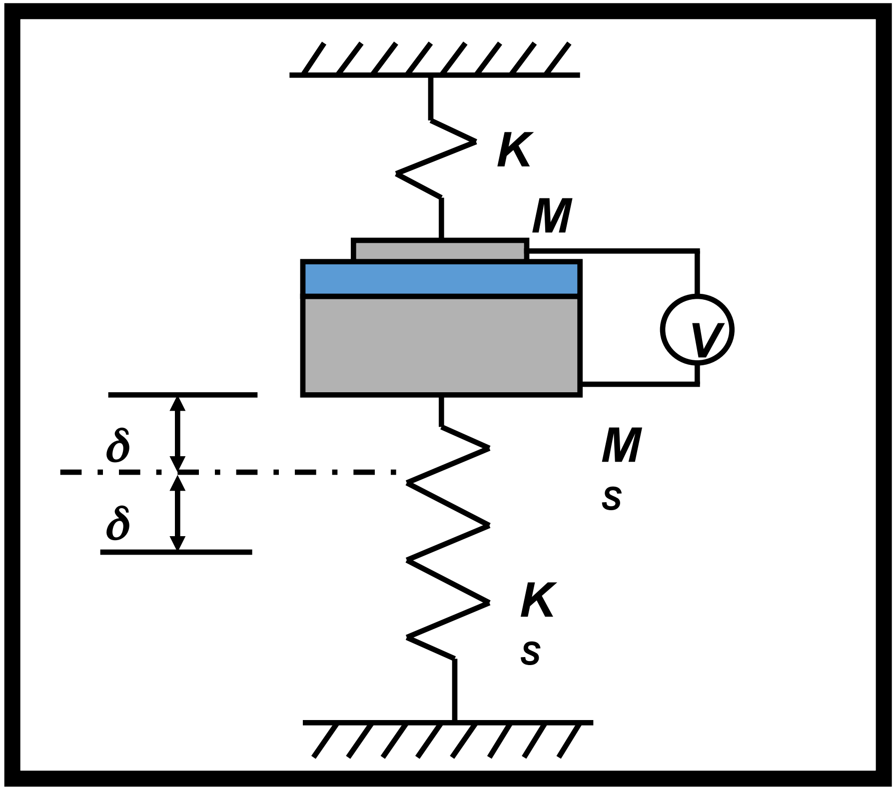
Principle used here: Electrostatic pull-in and pull-out

Input Excitation (ω_s)



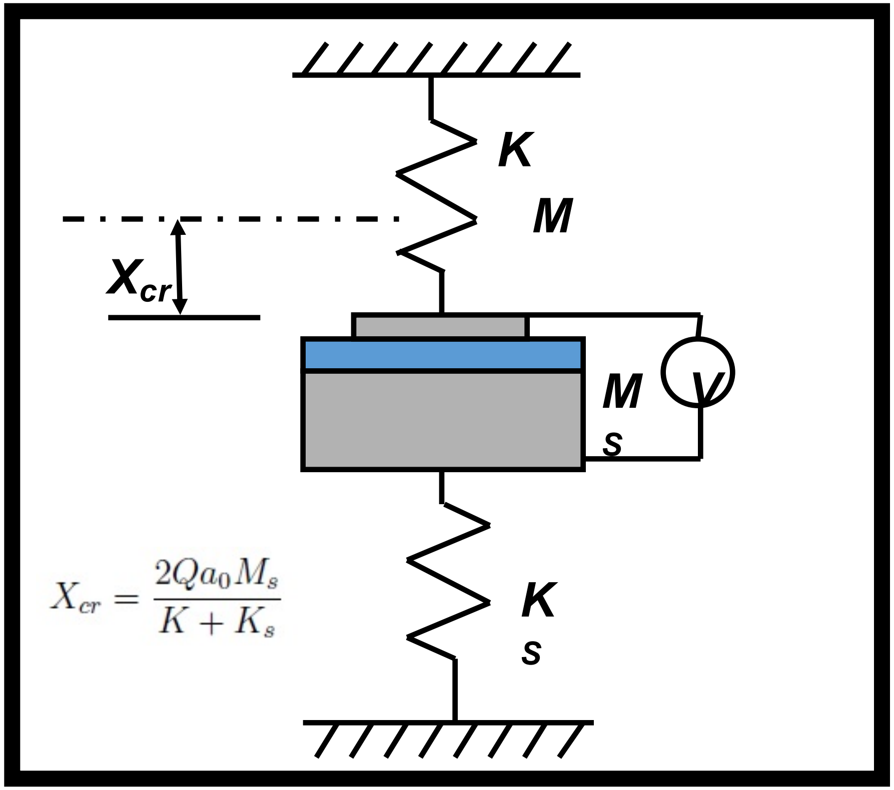
Frequency-up Energy Harvester

Pull-in



δ – max displacement of low frequency oscillator

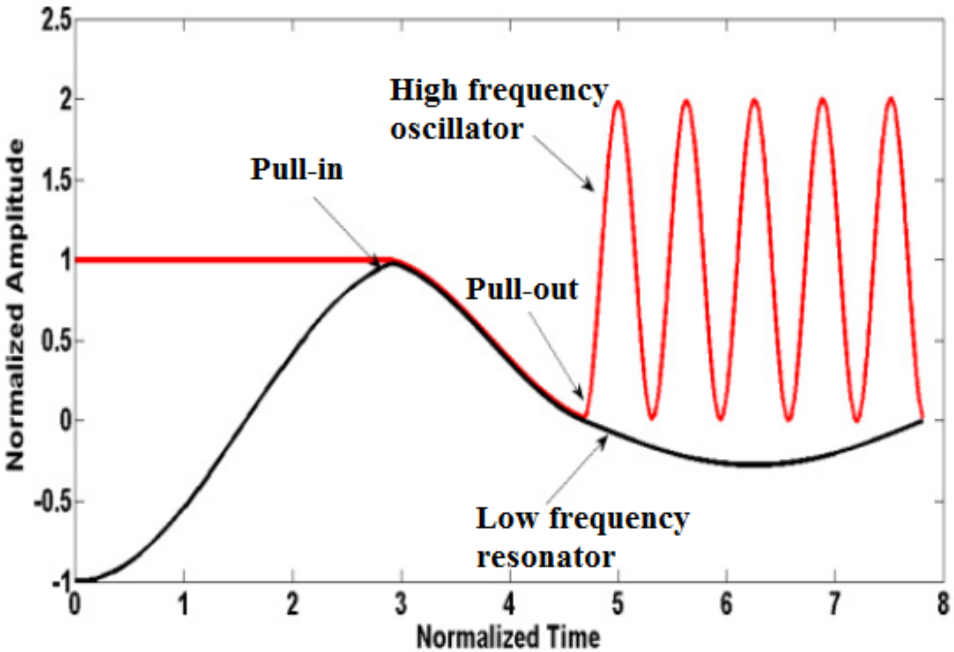
Pull-out



$$X_{cr} = \frac{2Qa_0M_s}{K+K_s}$$

Xcr – max displacement of high frequency oscillator before pull-out

Frequency-up Energy Harvester



S. Houri, 2014

$$F_{elec} = \frac{\varepsilon_0 A V^2}{2(\frac{h}{\varepsilon_r} + X)^2}$$

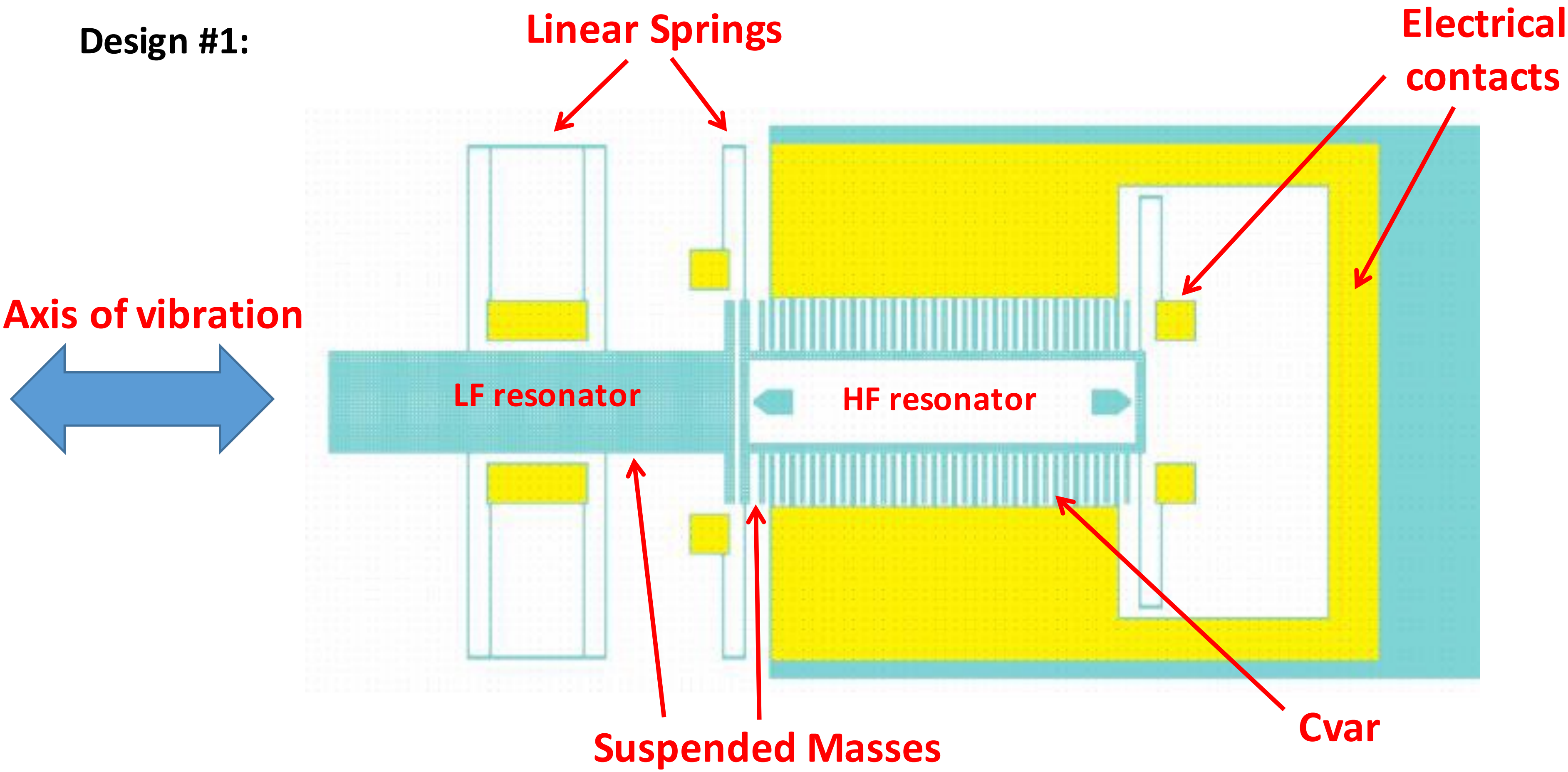
$$F_{elastic} = K \cdot X$$

Transmitted energy: $E_T \approx K X_{cr} (\frac{X_{cr}}{2} - \frac{3h}{\varepsilon_r})$

Frequency-up Energy Harvester

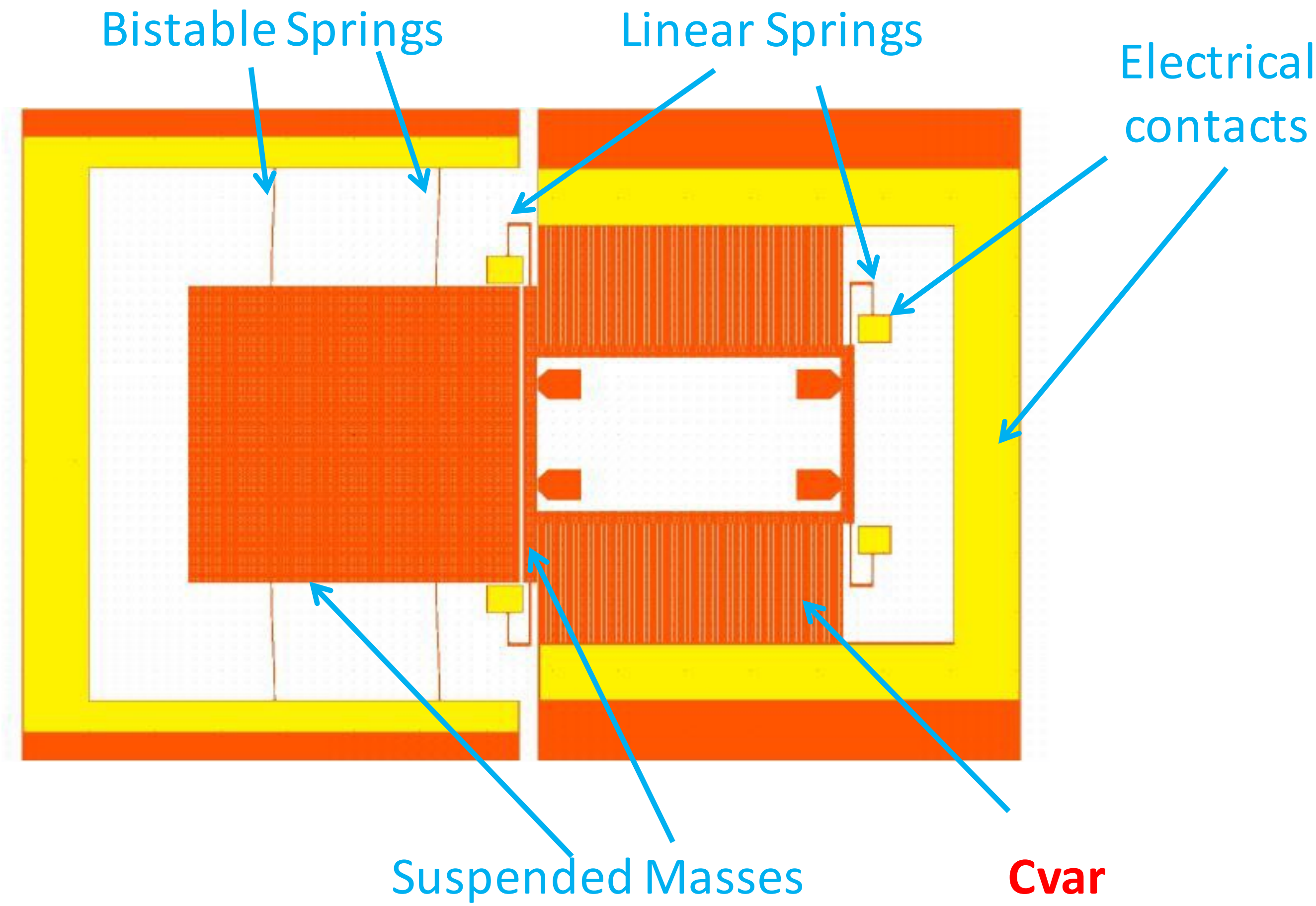
Principle: seismic oscillator gets excited from external medium and transmits energy to high frequency oscillator, which generates electricity

Design #1:



Frequency-up Energy Harvester

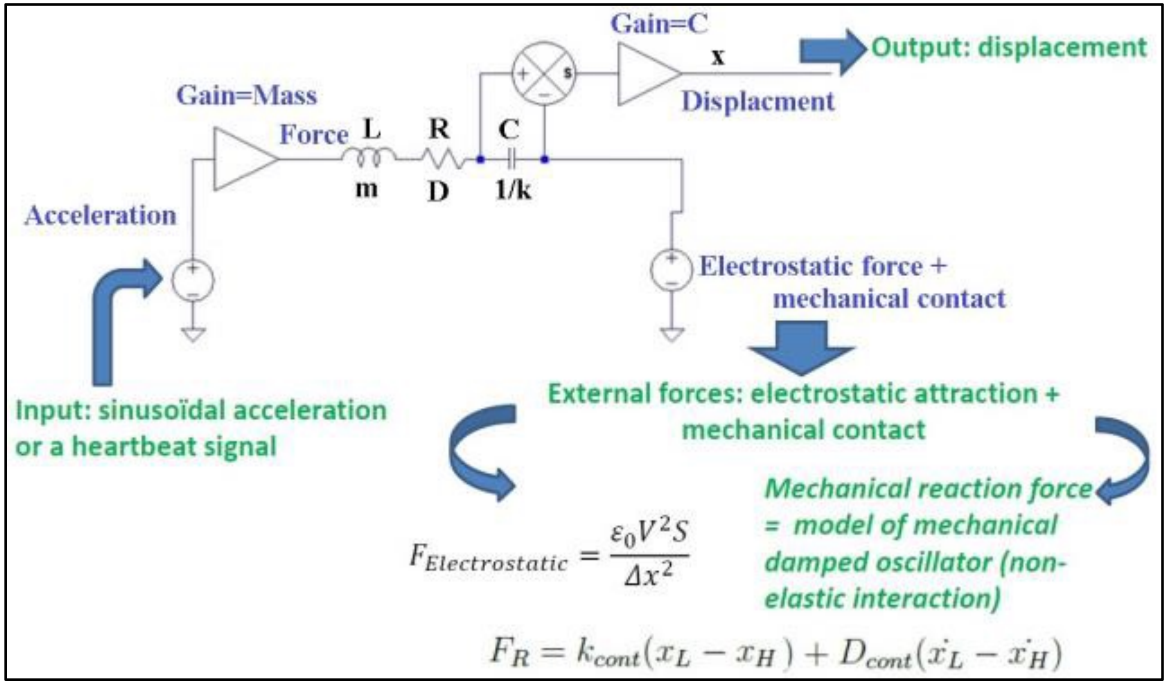
Design #2:



Frequency-up Energy Harvester

Modelling and simulation:

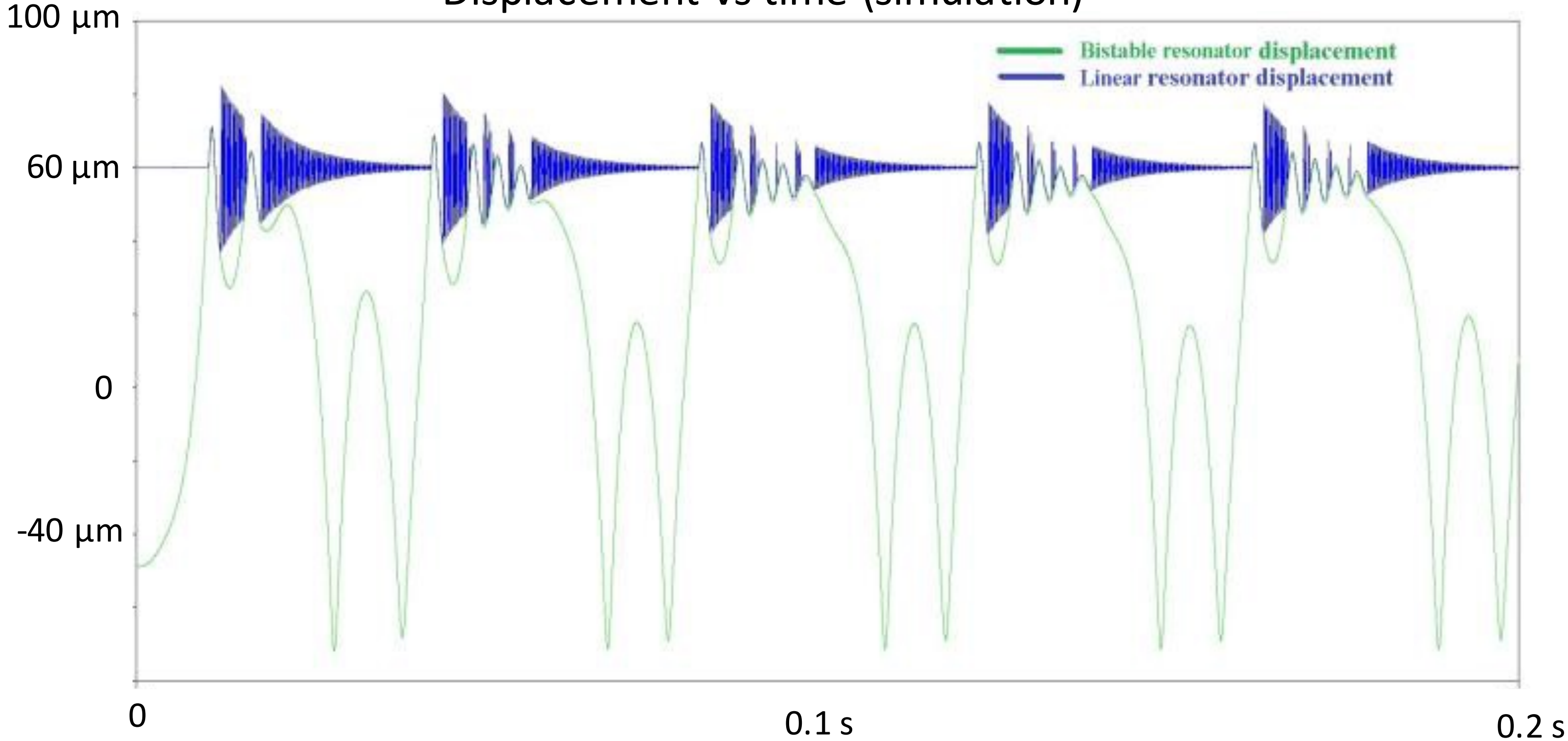
Example of one oscillator



Full model: 2 mechanically coupled oscillators + electrostatic attraction

Frequency-up Energy Harvester

Displacement vs time (simulation)

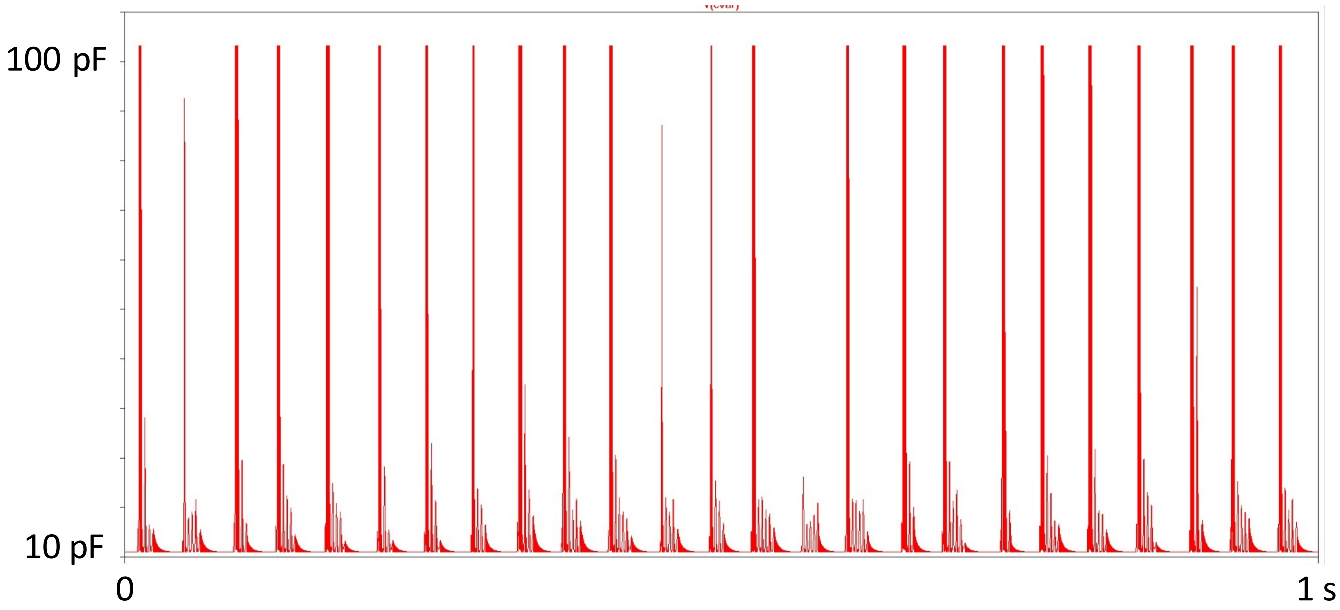


Excitation: sine @ 25Hz, 1g amplitude $M_{bistable}$=220mg, f_{HF}=4000Hz Vbias=1.2V

- Excitation at low frequency (close to heartbeat)
- Frequency up-conversion is observed
- Energy transfer as a result of pull-in and pull-out

Frequency-up Energy Harvester

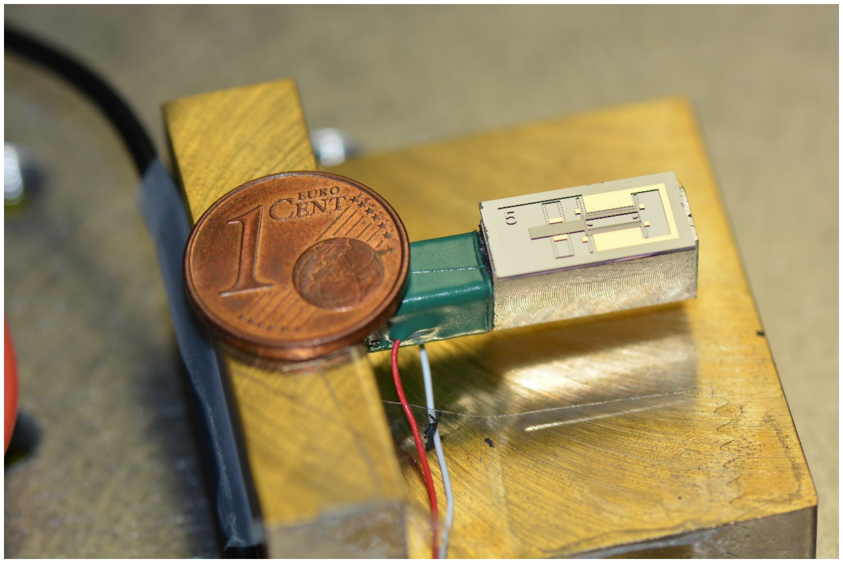
Capacitance vs time (simulation)

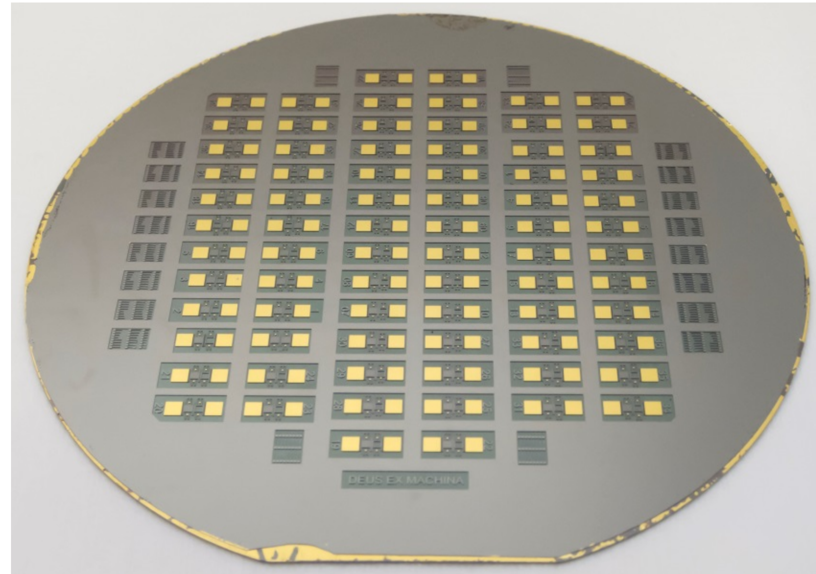


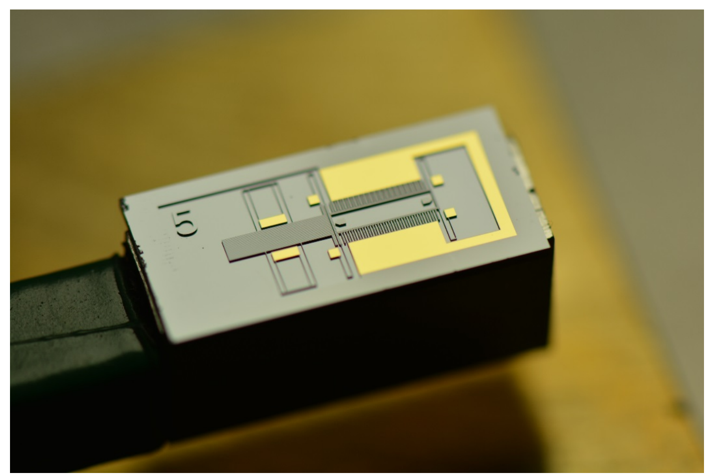
- Capacitance variation between 10pF and 100pF
- Good periodicity of variation
- Harvested average power: 1.5 µW

Frequency-up Energy Harvester

Fabricated devices:







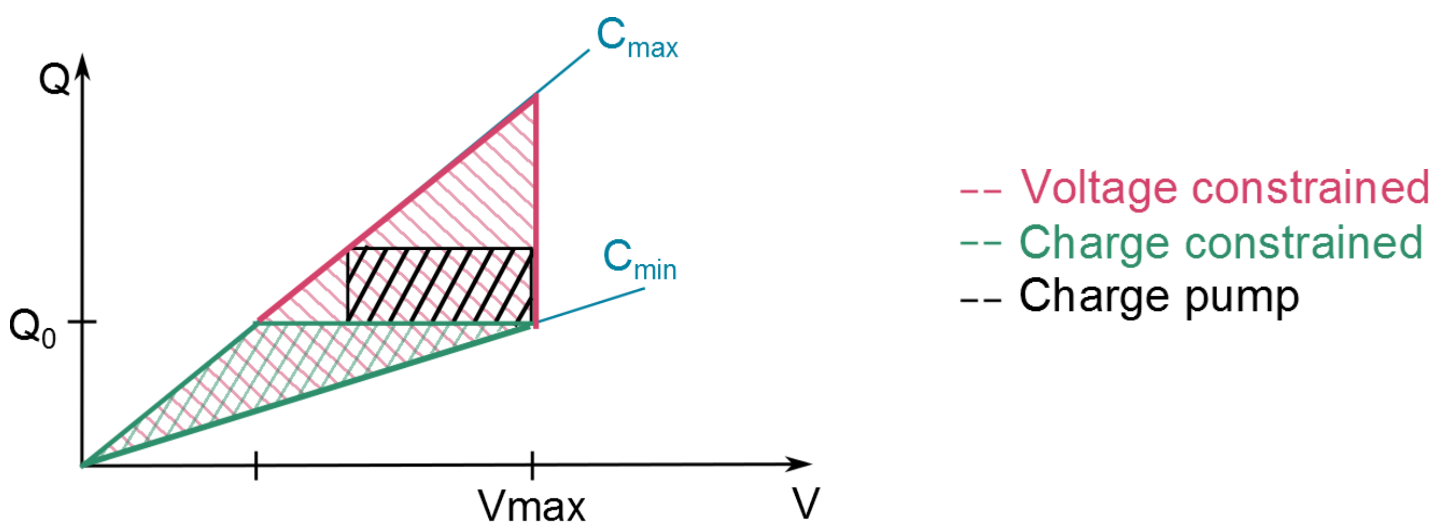
To be tested soon!

Interface circuits without magnetic components [Ms. Jie Wei Ph.D work]

Requirements for pacemaker application:

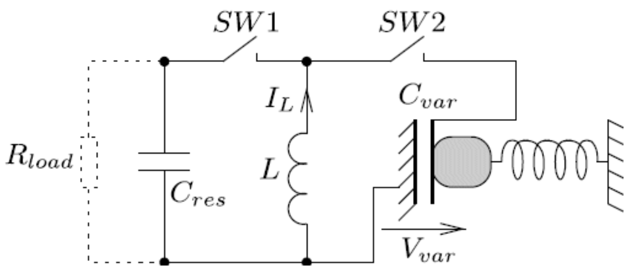
- Low power consumption & high efficiency at microwatt scale
- No magnetic components
- High reliability

Typical Charge-Voltage Diagram

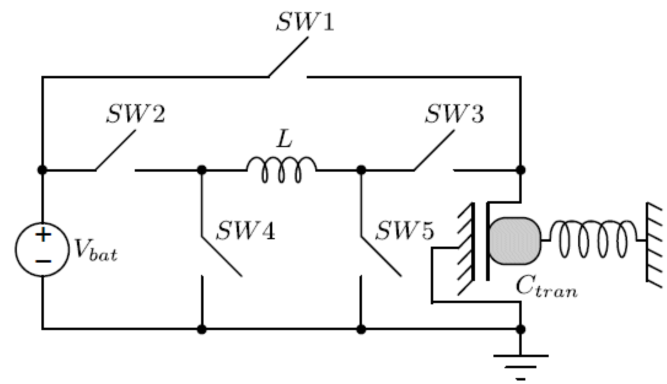


Interface Circuits

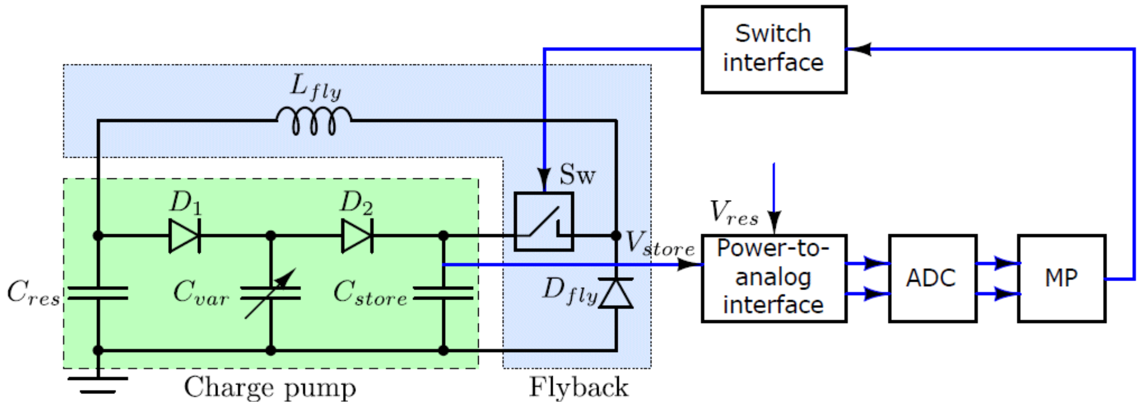
State of the Art:



Meninger et al., 2001



Torres et al., 2006

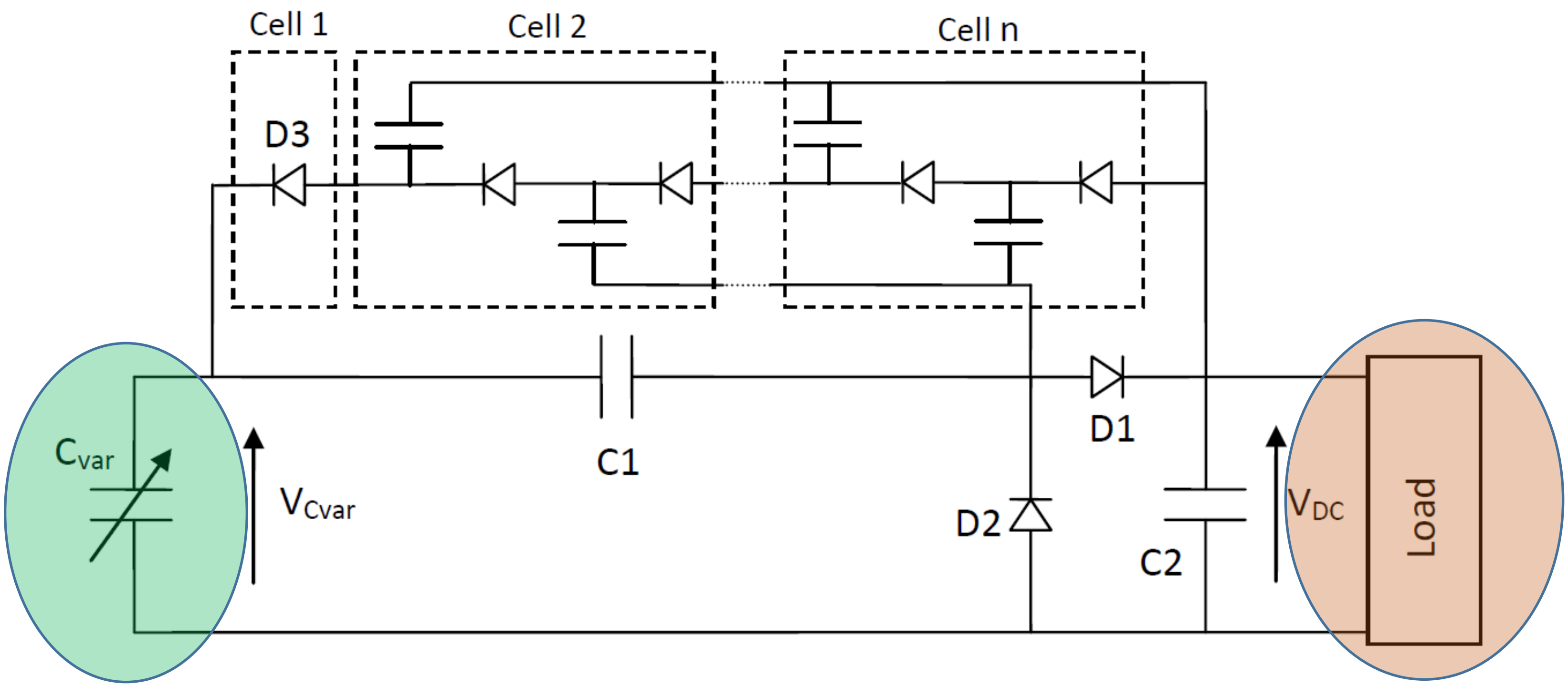


Yen et al., 2005

→ **Very challenging implementation at microwatt scale!**

Interface Circuits

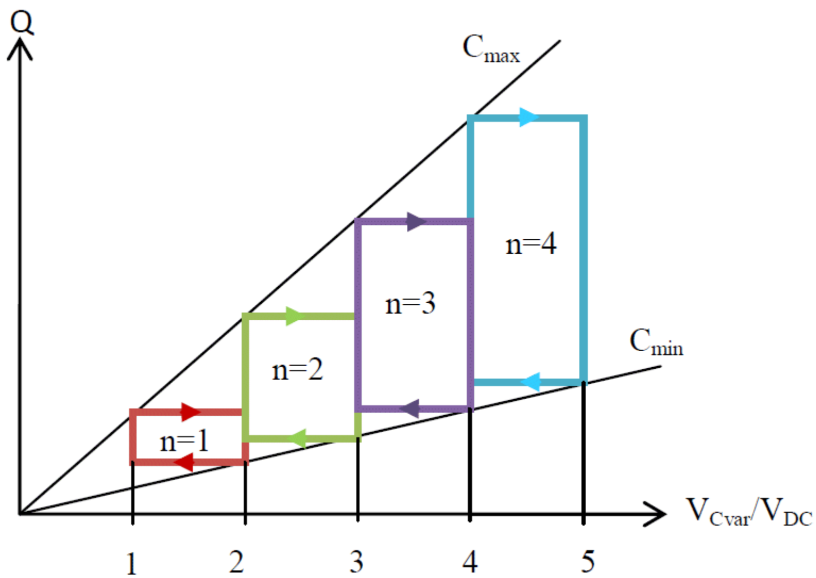
Proposed interface circuit:



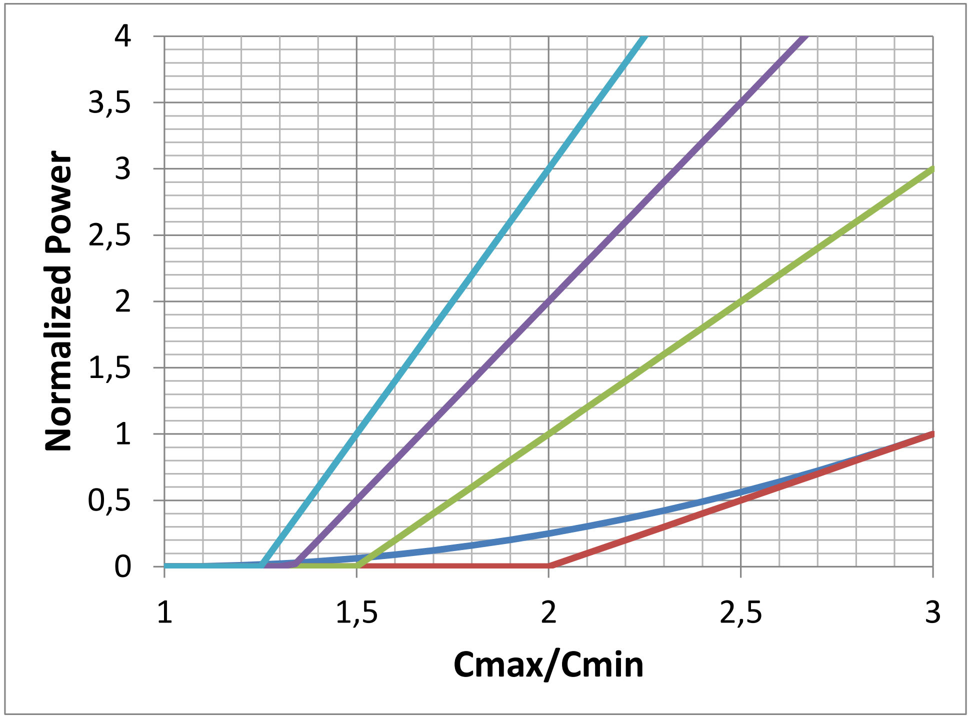
DC bias: $V_{C1} = n \cdot V_{DC}$

E. Lefeuvre, Patent n°WO2016009087A1, 2014

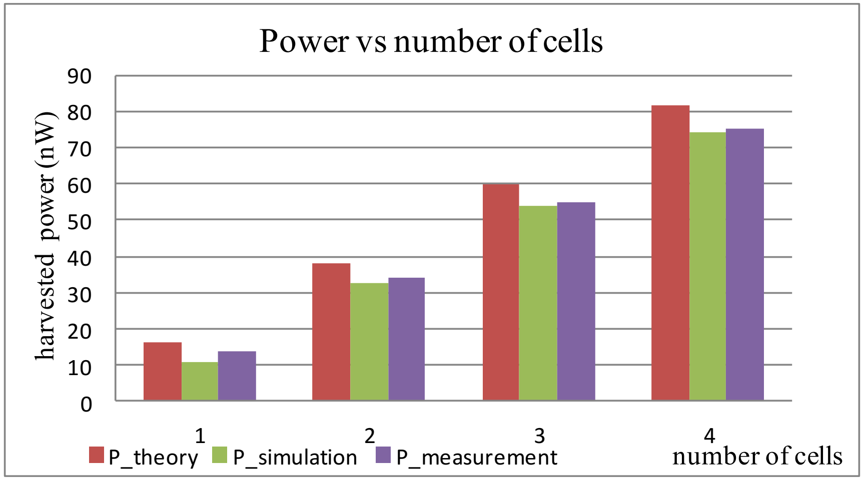
Q-V Cycles and Power:



$$W_{cycle} = n \cdot V_{Cstore}^2 \cdot C_{min} \left(\frac{C_{max}}{C_{min}} - \frac{n+1}{n} \right)$$



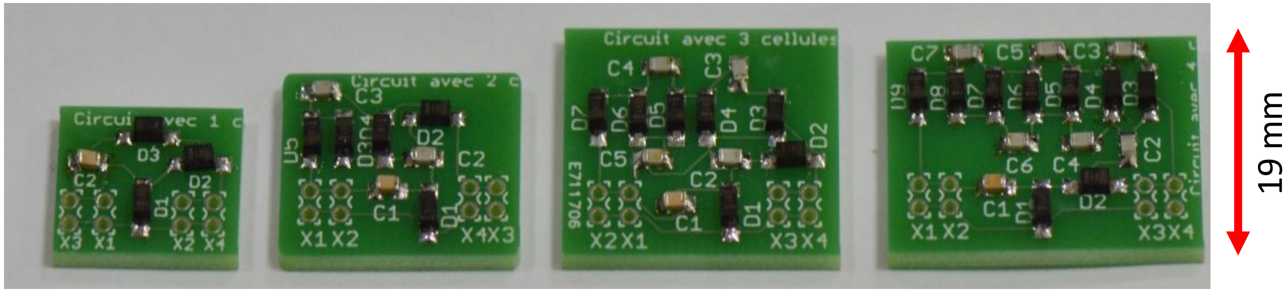
Experimental results: (Vcstore = 3.3 V)



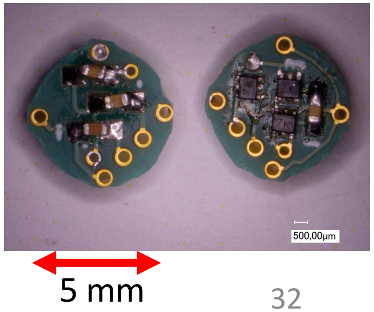
Efficiency

n Cells	1	2	3	4
Theory	76.7%			
Simul.	74.7%	74.7%	73.7%	73.5%
Exp.	76.6%	76.3%	76.3%	75.0%

n=1 n=2 n=3 n=4



n=3



SUMMARY

- New **3D** Electrostatic **Energy harvester** with high energy density ($\sim$ 70 μW/cm^3)
  (Sarah Risquez Ph.D. work)

- New **Frequency-up** Electrostatic Energy Harvester concept
  (Bogdan Vysotskyi Ph.D. Work)

- New **ultra-low power interface circuit** (76% efficiency at 10 nanowatts average power!)
  (Jie Wei Ph.D. work)

Remaining challenges for pacemaker application:

- Knowledge of human heart wall acceleration
- Lifetime of the device (20 years, +600 million hearbeat)
- Reliability
- Cost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