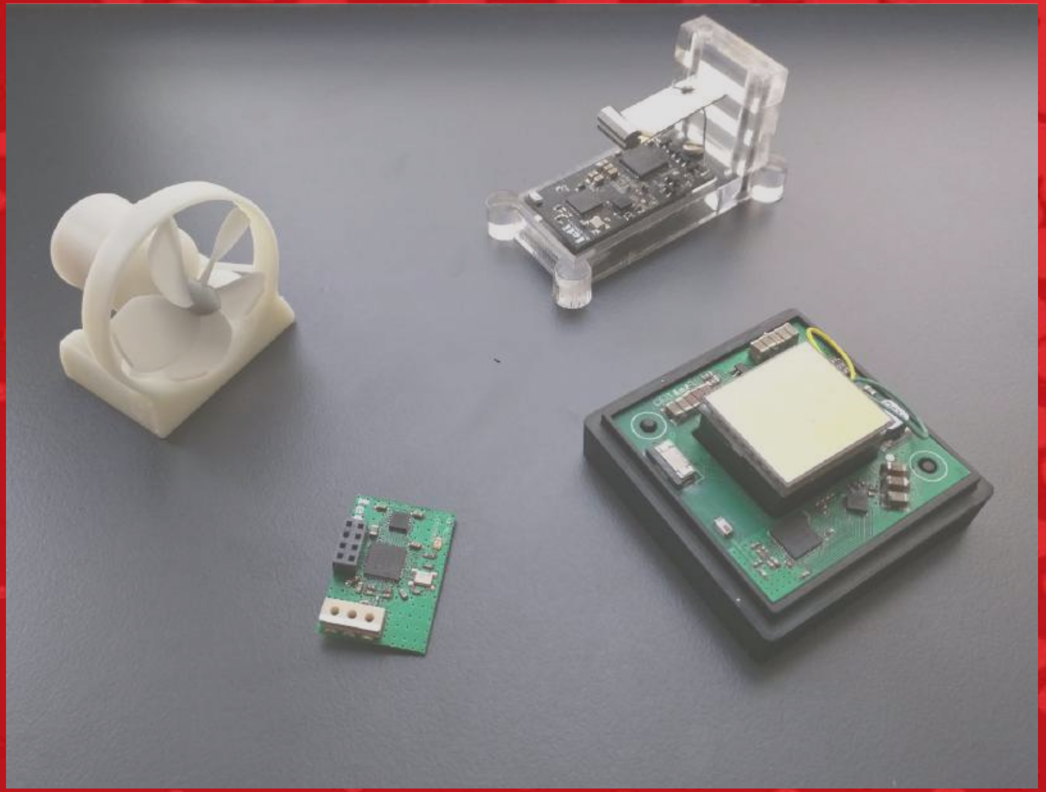


DE LA RECHERCHE À L'INDUSTRIE

# Web-Séminaire CRESITT - "Récupération d'énergie pour les petits systèmes"

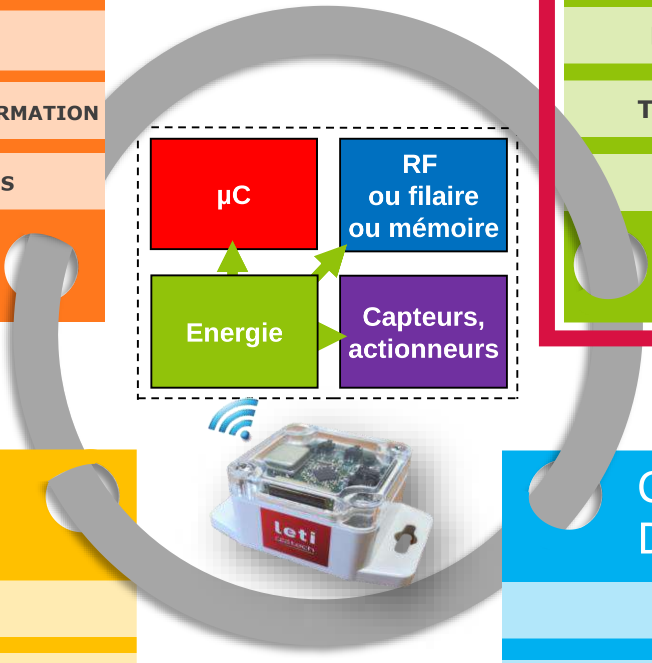
7 Juillet 2020

Pierre Gasnier – Leti/DSYS/SSCE/LAIC

# Research axes of the LAIC laboratory

- « **L**aboratoire **A**utonomie et **I**ntégration de **C**apteurs » (LAIC) @ Leti / System Division

**HAUTES PERFORMANCES**
- Datalogging - Enregistreurs
- Traitement et Transmission de l'Information
- Hautes fréquences et précisions




**AUTONOMIE**
- Electronique basse consommation
- Transmission de Puissance Sans Fil
- Récupération d'énergie

Theme carried out **since 2003** : numerous **industrial projects** and an increase in **academic partnerships** (thesis in particular)

**ENVIRONNEMENTS COMPLEXES**
- Environnements sévères
- Environnements contraints

**CAPTEURS DISTRIBUES**
- Capteurs innovants
- Capteurs distribués
- Surfaces Sensibles
- Intelligence distribuée

# Outline

**Introduction : Energy Harvesting, dream and reality**

**1** **Quantitative/qualitative aspects, system view and challenges**

**2** **Mechanical Energy Harvesters**
( + power management circuits)

**3** **Flow-driven Energy harvesters**

→ *Some general principles, State Of the Art, challenges + CEA examples*

**Conclusion**

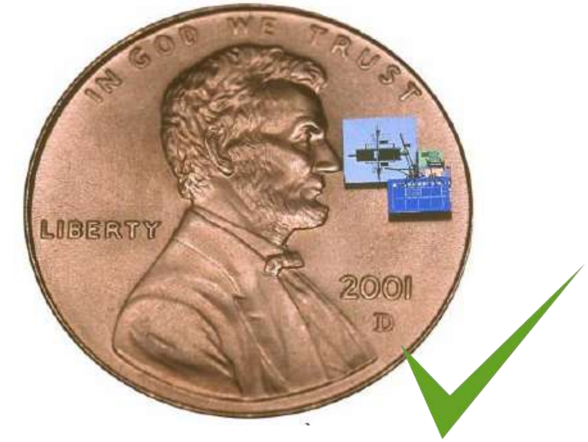
# Introduction

- **Energy Harvesting for small systems ? Let me google that for you …**

*Camille Pissarro « The **Harvest** » - 1882*


*Neil Young « **Harvest** » - 1972*

*Key ring Dynamo (Decathlon) → **generator***




*Berkeley « **Smart-Dust** » - 2002*

*16 mm$^3$ autonomous solar-powered sensor node*

- **Some "good" key words**

***Sporadic/intermittent/irregular***

***Opportunistic unintentional***

*Energy **Generators***

*Energy **harvesters***

***Autonomous** Wireless Sensor Node (**WSN**)*

***Battery-less***

*Energy **Scavengers***

***Micro power***

***Self-powered***

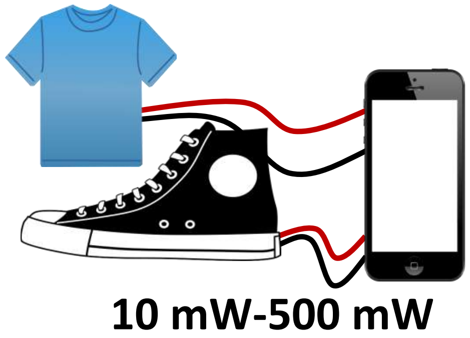
*Solar-**powered***

*Vibration-**powered***

*…*

# Introduction

- **Energy Harvesting : the dream**

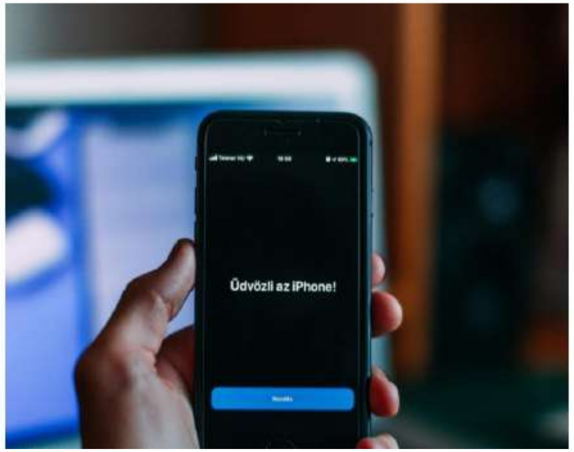



*"Shoes or clothes can recharge your iphone!"*

## Charge Your Cell Phone With Your Skin

April 29, 2014

A battery can charge your cell phones when they are in your pockets as they are a great way to convert your body heat into electricity that can lead to the capabilities of the mobile phone to charge themselves when they are in your pockets. The Massachusetts Institute of Technology researchers have developed that the self-charging batteries are button-sized and they can search from the energy even if the temperature is low. The devices can charge themselves even if the temperature is lower than the heat-harvesting technologies and Dr. Gang Chen said the technology can lead the new mobile phone batteries that can charge the devices without plugging them into the outlets.




incharged.com

AUGUST 12, 2014

## Mobile phones come alive with the sound of music, thanks to nanogenerators

by Queen Mary, University of London

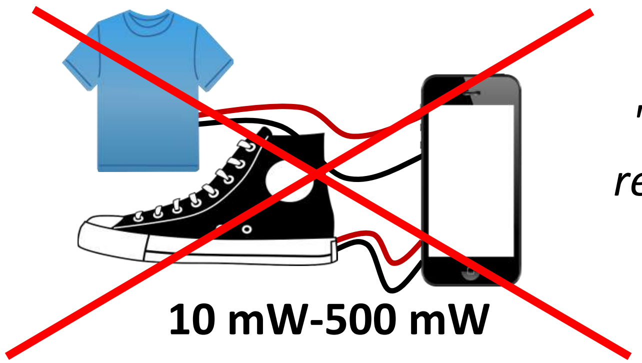
Credit: Peter Griffin/Public Domain

Charging mobile phones with sound, like chants from at football ground, could become a reality, according to a new collaboration between scientists from Queen Mary University of London and Nokia.

phys.org

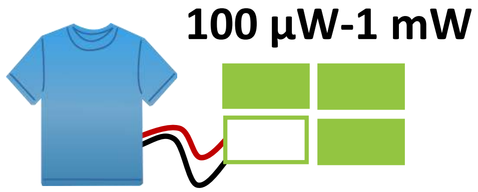
# Introduction

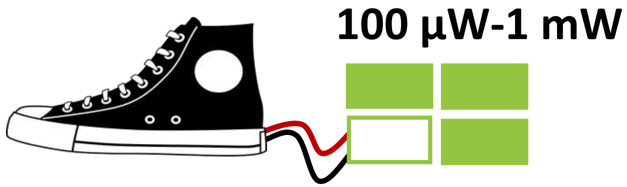
- **Energy Harvesting : the dream**




*"Shoes or clothes can recharge your iphone!"*

- **Energy Harvesting : the reality …**



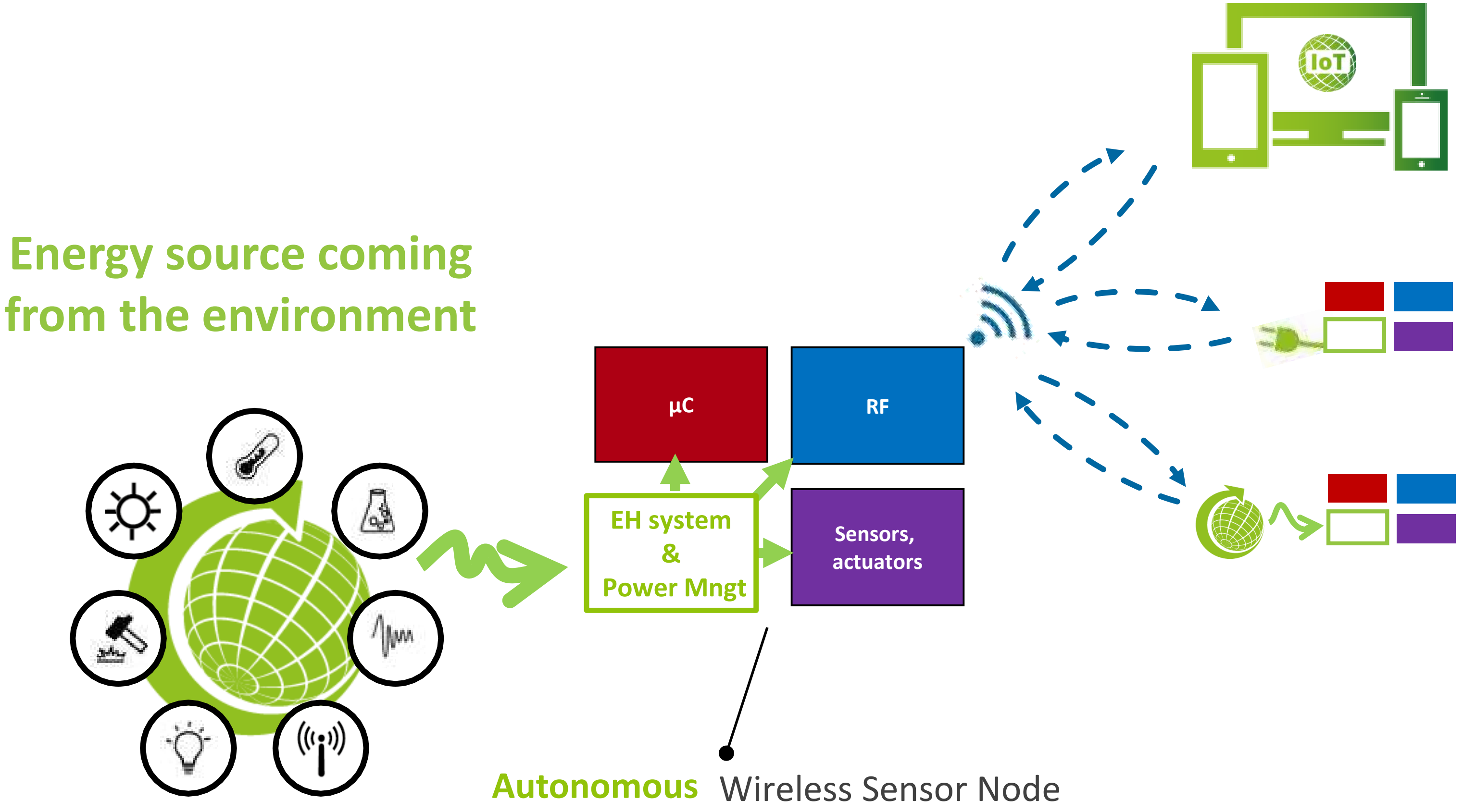




*"Tee-shirts could power an **optimized and low power** wireless cardio"*

*"Shoes could power **optimized and low power** wireless force sensors"*

# Introduction

- **Towards Autonomous Wireless Sensor Nodes (WSN) :**



# Outline

Introduction : Energy Harvesting, dream and reality

1 Quantitative/qualitative aspects, system view and challenges

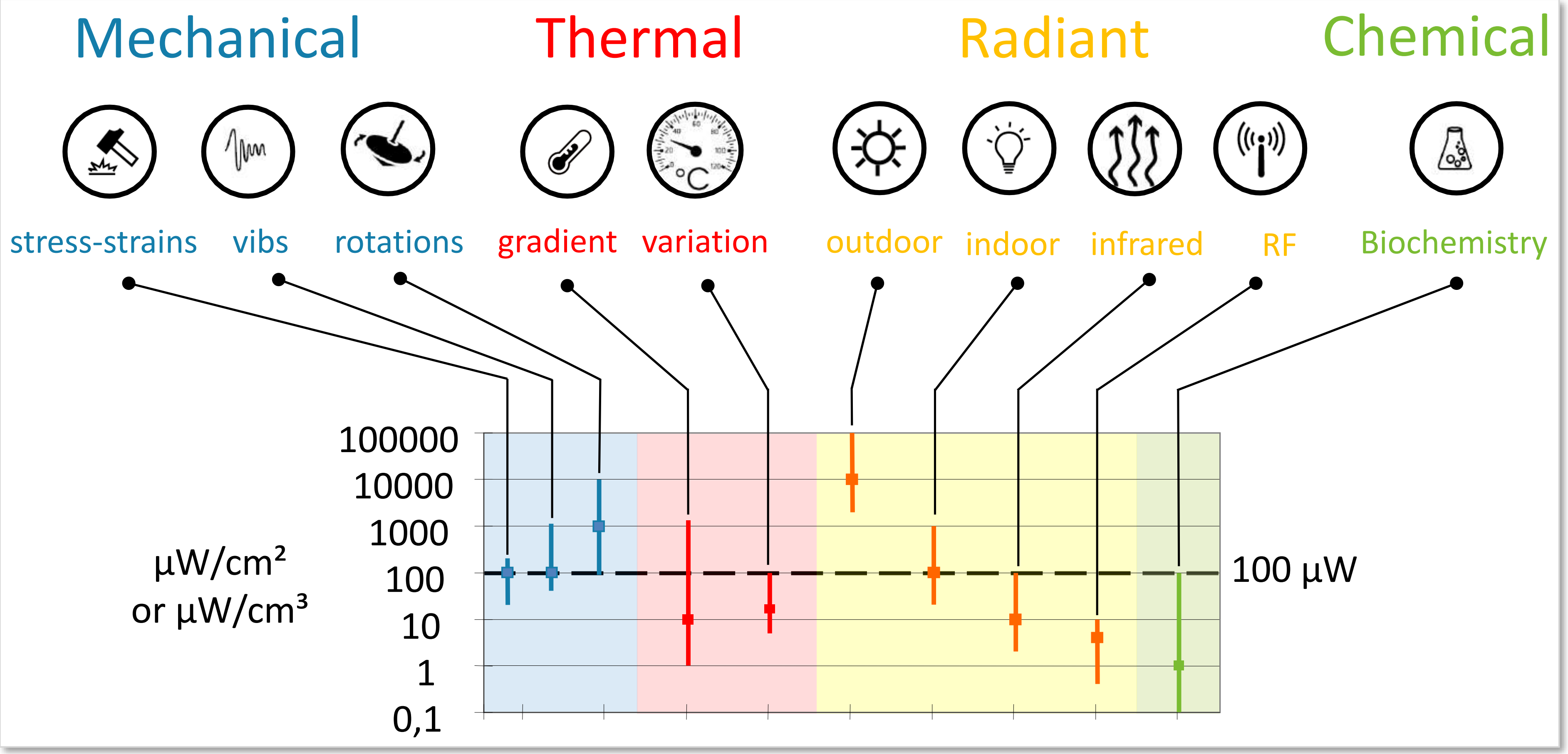
2 Mechanical Energy Harvesters
( + power management circuits)

3 Flow-driven Energy harvesters

Conclusion

# Quantitative/qualitative aspects

- **Quantitative aspect : harvestable powers (order of magnitude)**




**Radiant energy with PV cells :**

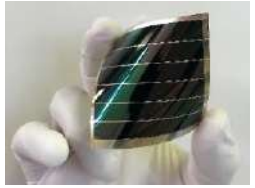
→ Crystalline Silicon vs Amorphous Silicon

→ Numerous suppliers : Panasonic/Amorton, 3G solar, PowerFilm, …

→ best power densities

→ Small scale indoor PV : ≈10-15µW/cm² typ @200Lux

Amorphous (Amorton)

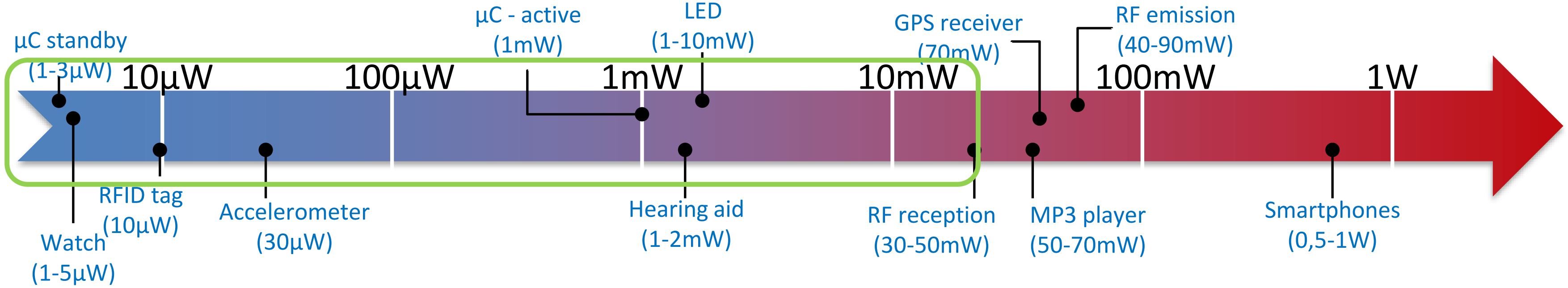


OPV (INES)

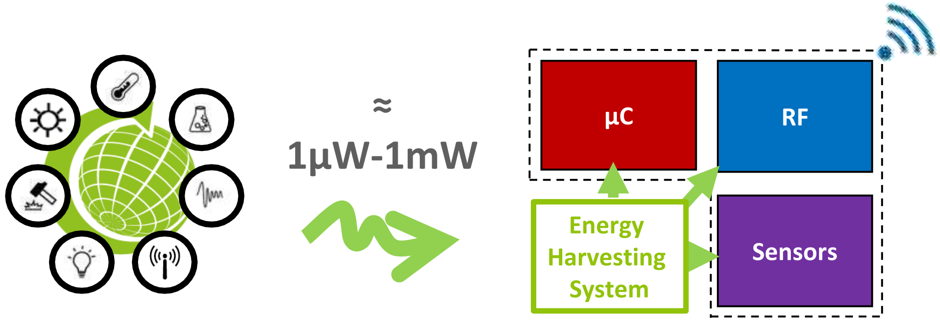
**… See following talk by John Fiske ARMOR**

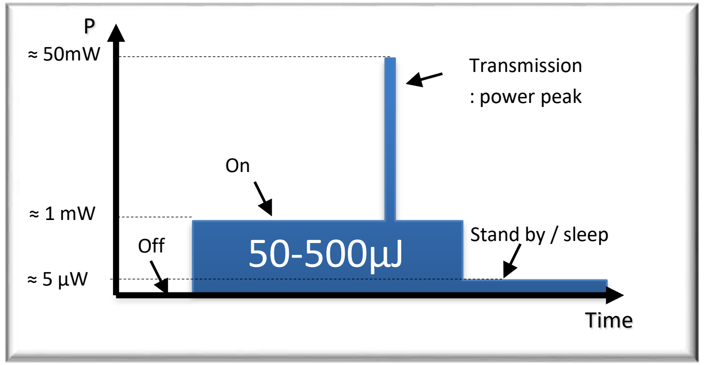
# Quantitative/qualitative aspects

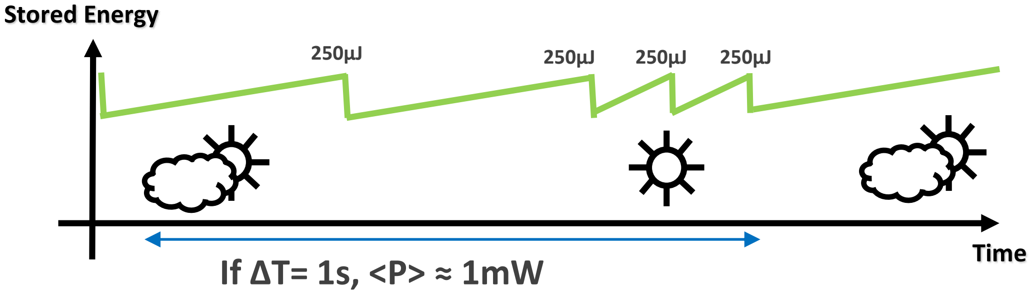
- **Quantitative aspect : the power demand**




- **Qualitative aspect : input power generally intermittent and irregular**




→ **Storing the energy is necessary**

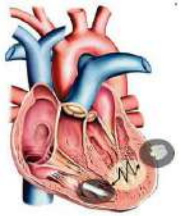
→ **Asynchronous operation of the WSN generally required**

# Quantitative/qualitative aspects

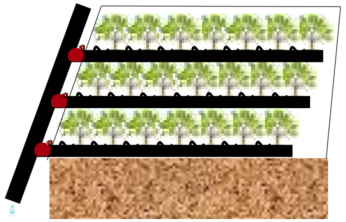
- **Energy harvesting when it is unavoidable :**
  - harsh environments (high temperature…)
  - location difficult to access
  - many WSNs : changing the batteries is expensive (maintenance costs)
  - long-life WSN (>10-20 years), sometimes in addition to a primary cell …

***Vehicle health monitoring, Medical applications…***

**Harsh Environments** - ©Microturbo



***Smart-Buildings, industrial maintenance…***

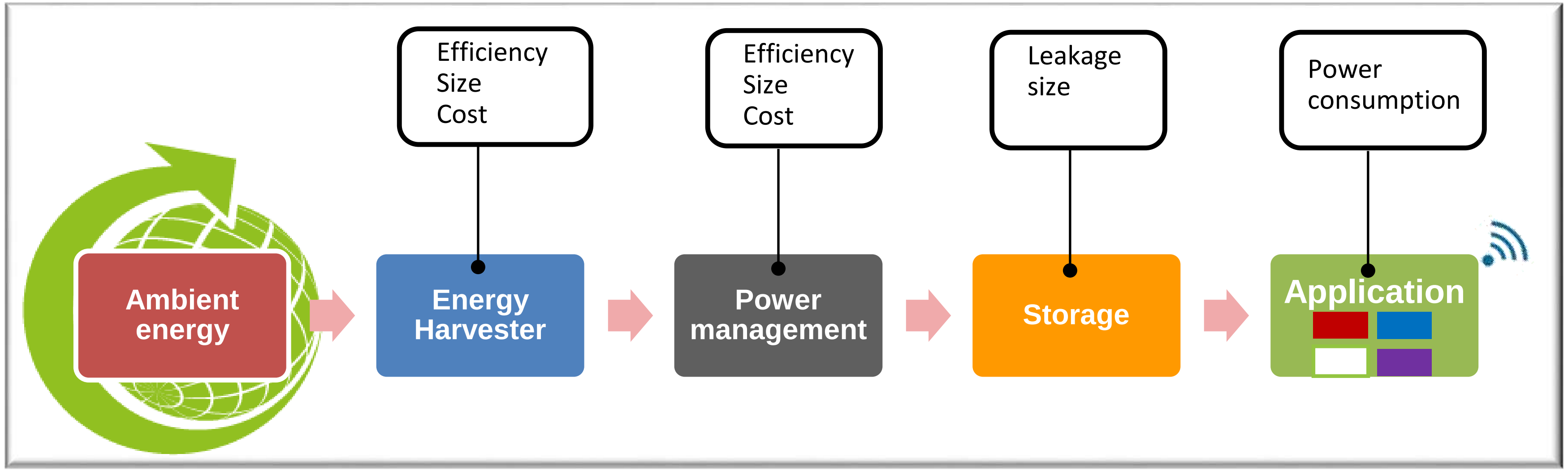


**Abandoned Sensors**- ©ITK

→ **Energy harvesting technologies are still linked to specific applications**

# Introduction : the system view

- **From ambient energy to autonomous devices**




- Constraints and optimizations on the complete chain: the importance of a "**system view**"
- Harvesters **dedicated** to the environment, **power management circuits** dedicated to the harvester
- Strong impact of the power management circuits on the efficiency /volume : **global power density**
- **An approach often adopted :**

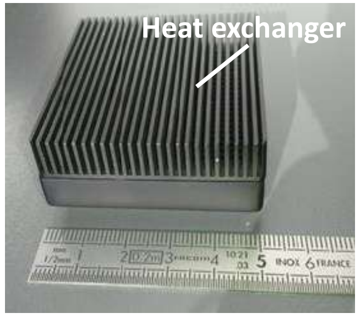
1 **Power demand** (µW) and WSN operating mode ? ⇨ WSN optimization

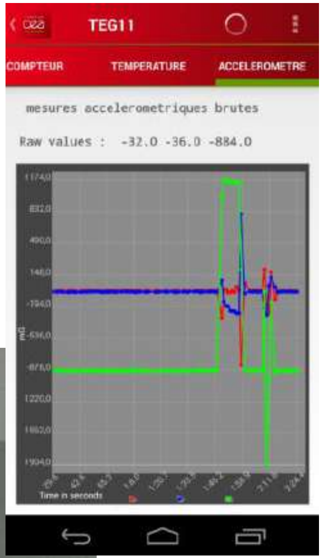
2 **The environment :** input energy and volume allocated to the harvester ? ⇨ Design of the harvester

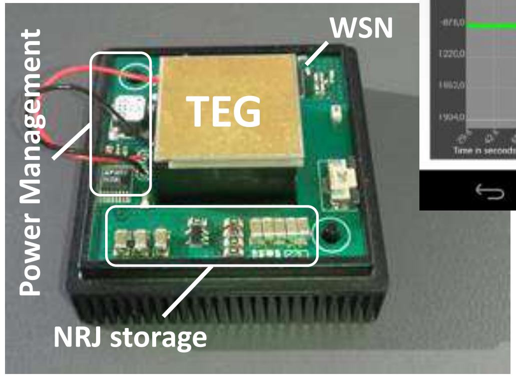
# Introduction : example of autonomous sensors powered by EH

- **Energy Harvester + Power management + Low-power WSN**

## Thermally-powered devices

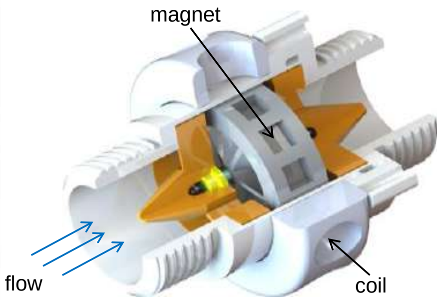


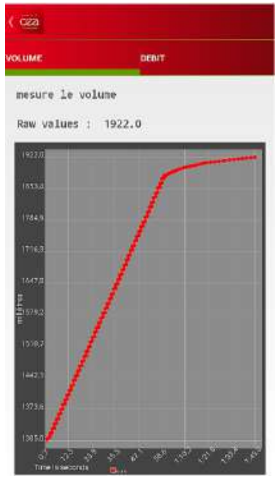



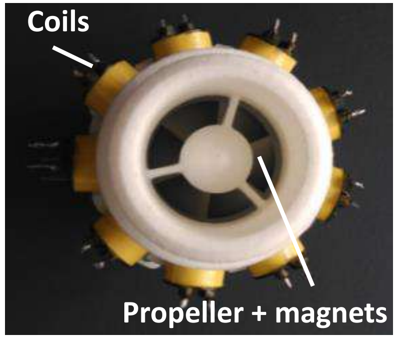




Thermoelectric EH + PMC + BLE node =
Temperature sensors & accelerometers
powered by thermal energy

## Airflow/Waterflow-powered devices

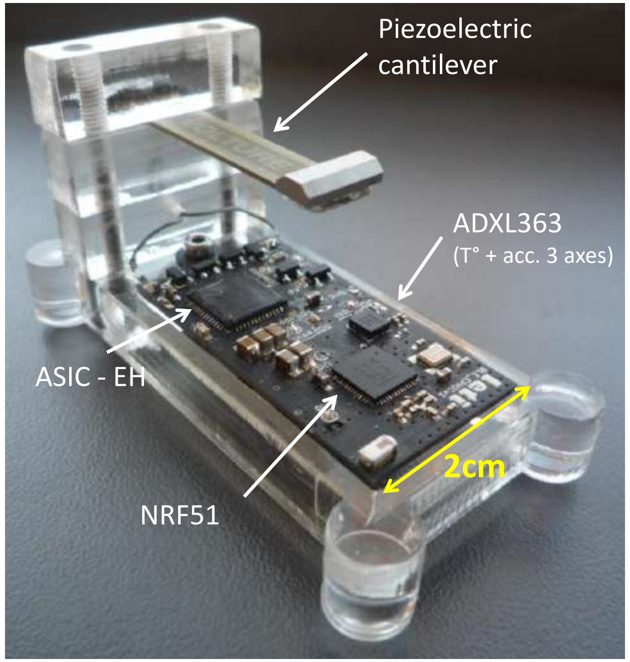



Turbine + PMC + BLE sensor node =
flowmeter powered by the water flow
⇨ connected irrigation

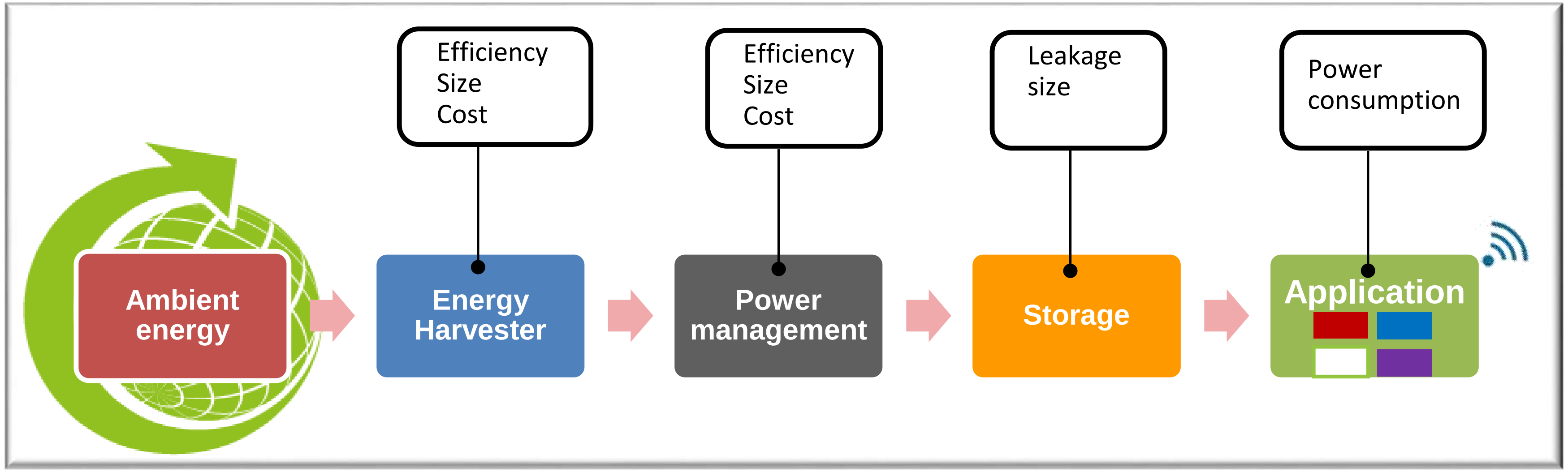
## Vibration-powered devices




Vibration energy harvester + PMC + RF =
Autonomous T°/acc° sensors
⇨ predictive maintenance

# Introduction : challenges

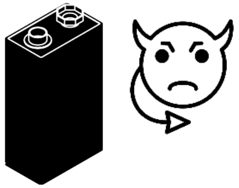
- **From ambient energy to autonomous devices**




- Main challenges :
  - their **power densities** or volumes … but WSN are consuming less and less
  - their **reliability** (particularly mechanical harvesters)
    - « Operational reliability » (Amplitude, frequency range, …)
    - Ageing and robustnest
  - their **costs**
  - their **environmental impact**

**we focus on these aspects**

… as compared with batteries



# Outline

Introduction : Energy Harvesting, dream and reality

1 Quantitative/qualitative aspects, system view and challenges

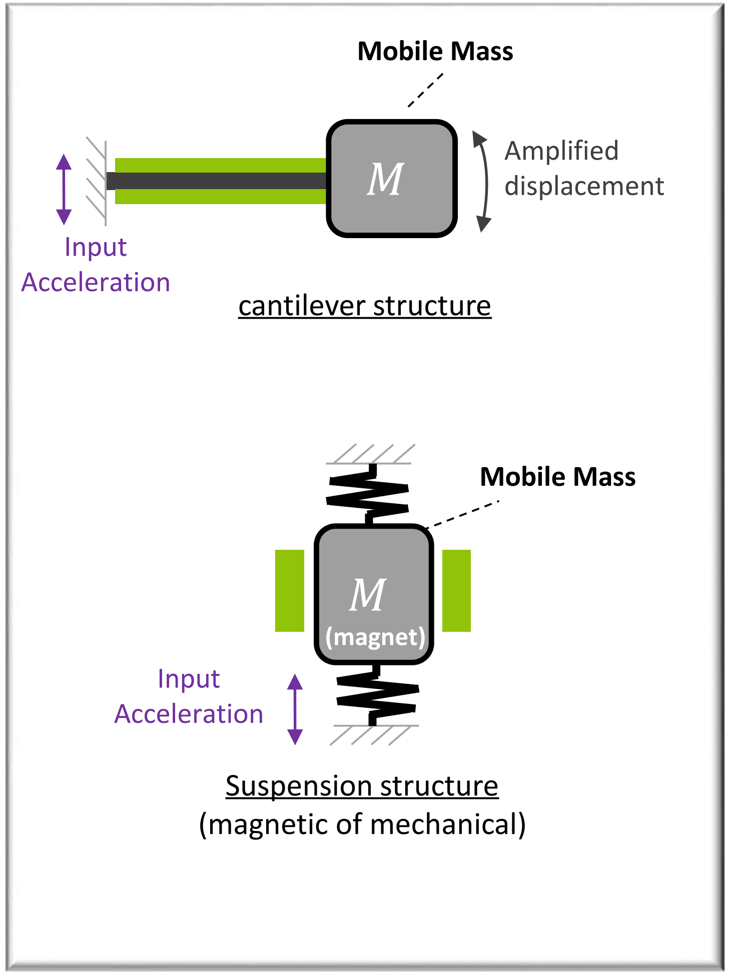
2 **Mechanical Energy Harvesters**
( + power management circuits)

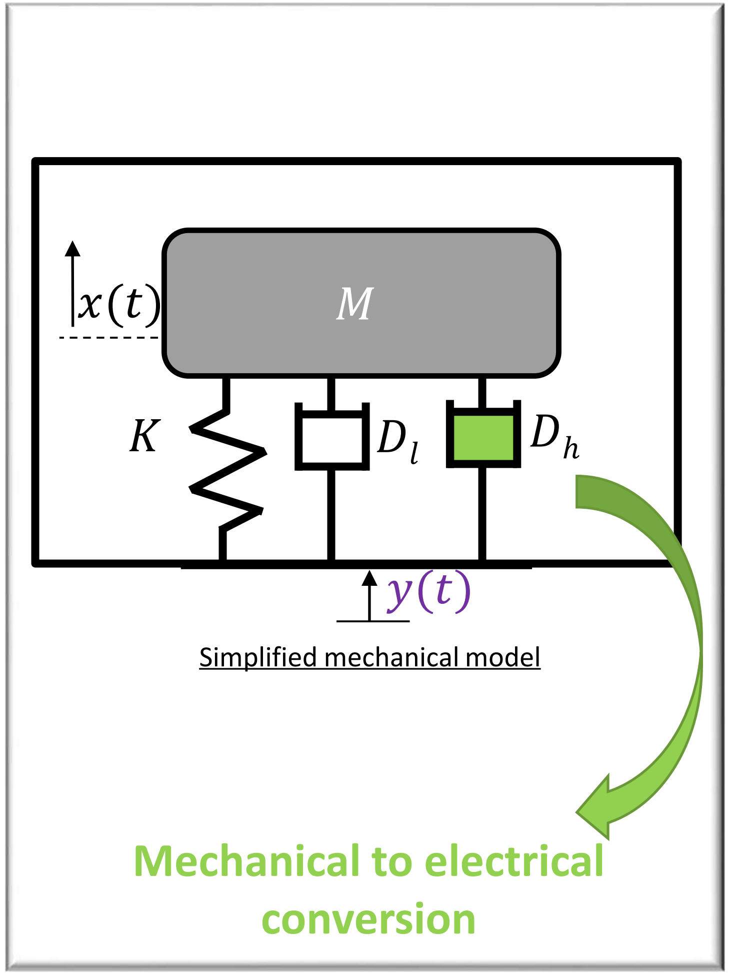
3 Flow-driven Energy harvesters

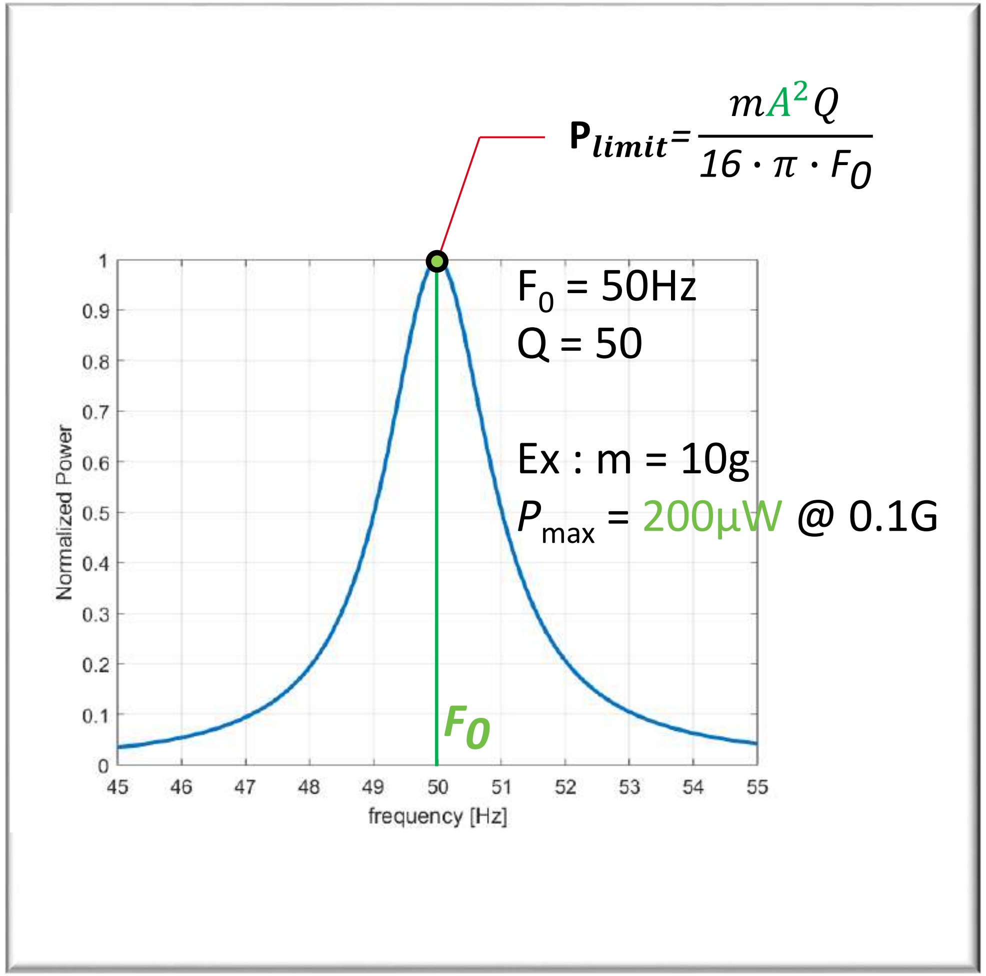
Conclusion

# Vibration Energy Harvesting : general principle

- Resonators (Mass – stiffness – Damper) with high power densities

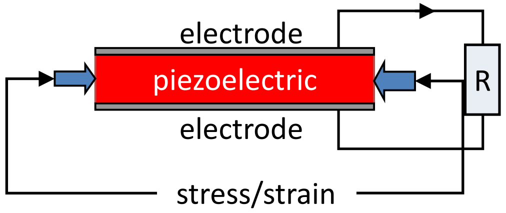
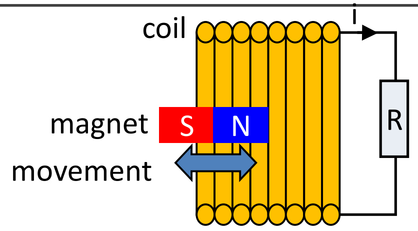
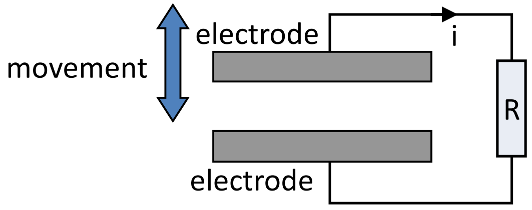


# Vibration Energy Harvesting : general principle

- **Mechanical to electrical conversion (transduction)**

| Piezoelectric | Electromagnetic | Electrostatic |
|---|---|---|
| Use of piezoelectric materials | Use of Lenz's law | Use of a variable capacitor |
|   |   |   |
| + high output voltages<br>+ high capacitances<br>+ no need to control any gap<br>- piezo = part of the mech. suspension<br>- Expensive material | + high output currents<br>+ conversion ≠ mechanical suspension :<br>- low output voltages<br>- coils are resistive at low frequencies<br>- hard to reduce coil dimensions | Very high output voltages<br>+ possibility to build low-cost systems<br>+ coupling coefficient easy to adjust<br>+ size reduction increases capacitances<br>- low capacitances<br>- high impact of parasitic capacitances |

**Vibrations**

- **Piezoelectric**
- **Electromagnetic**
- **Electrostatic**

**Rotations**

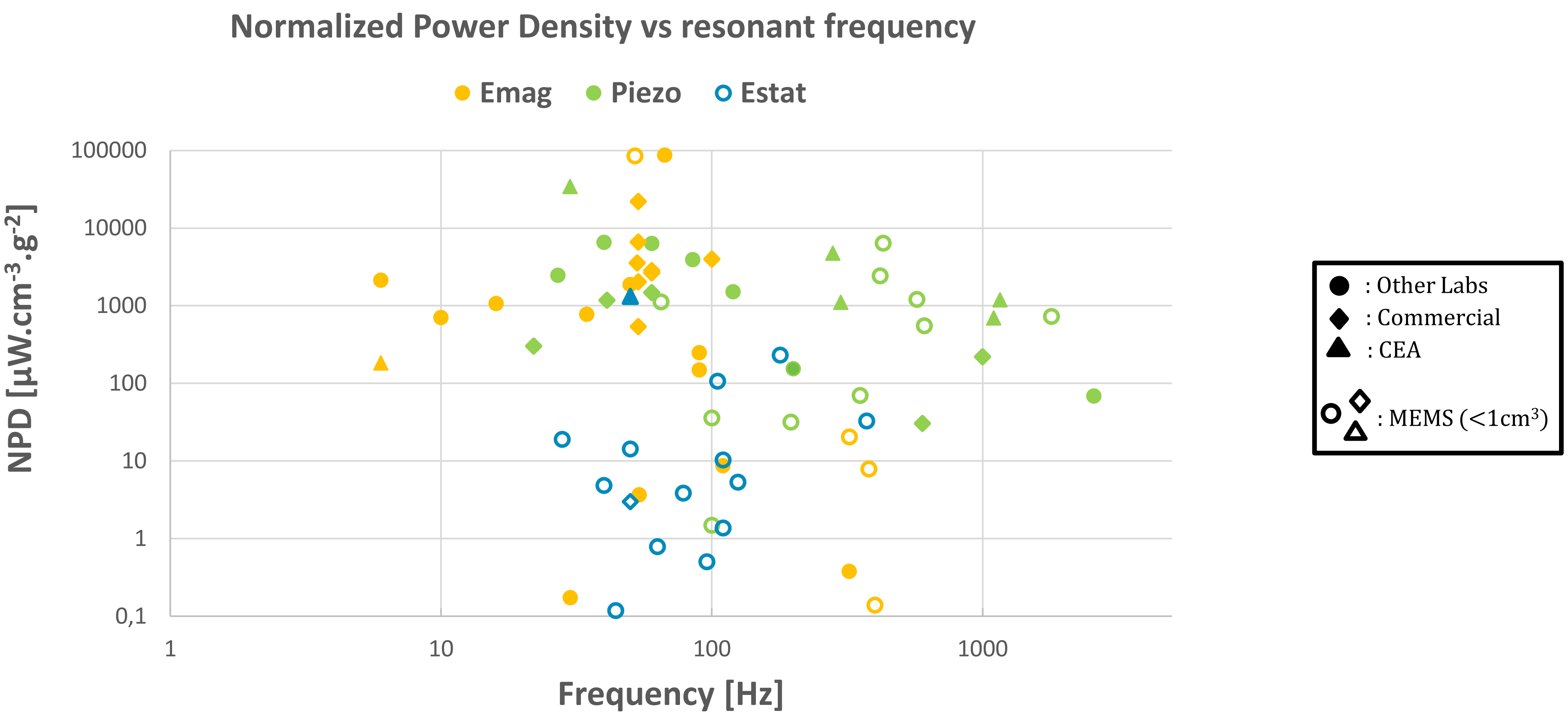
- **Electromagnetic**
- Electrostatic
- (Piezoelectric)

**Strains, stresses and shocks**

- **Piezoelectric**
- **Electromagnetic**
- Electrostatic

# Vibration Energy Harvesting : general principle

- **Power densities in practice …**




→ NPD Electromagnetic ≈ NPD Piezoelectric > NPD Electrostatic

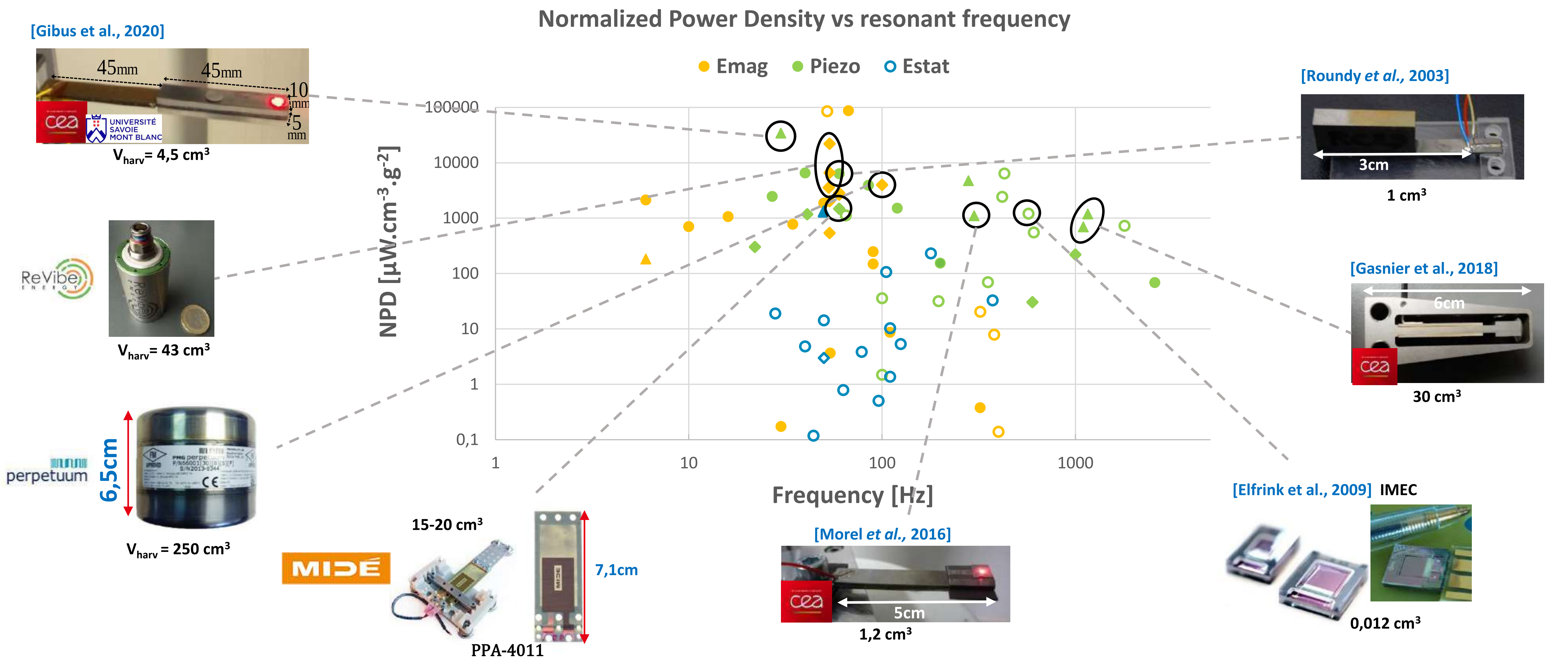
→ Electrostatic : NPD relatively low in practive but enables MEMS device (size reduction)

→ Operating frequencies : Electromagnetic ≈ 10–100Hz, Piezoelectric : 50-1000Hz

# Vibration Energy Harvesting : general principle

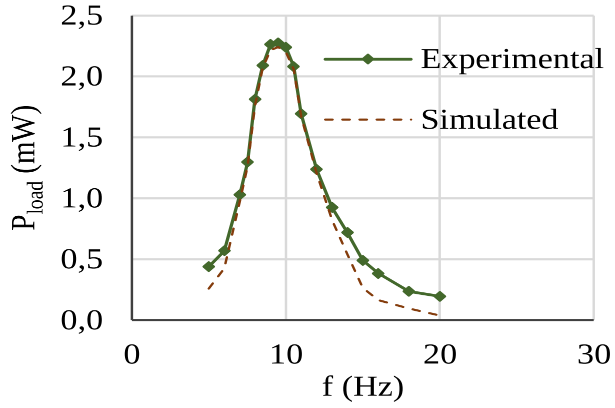
● : Other Labs
◆ : Commercial
▲ : CEA
○ ◇ △ : MEMS (<1cm³)

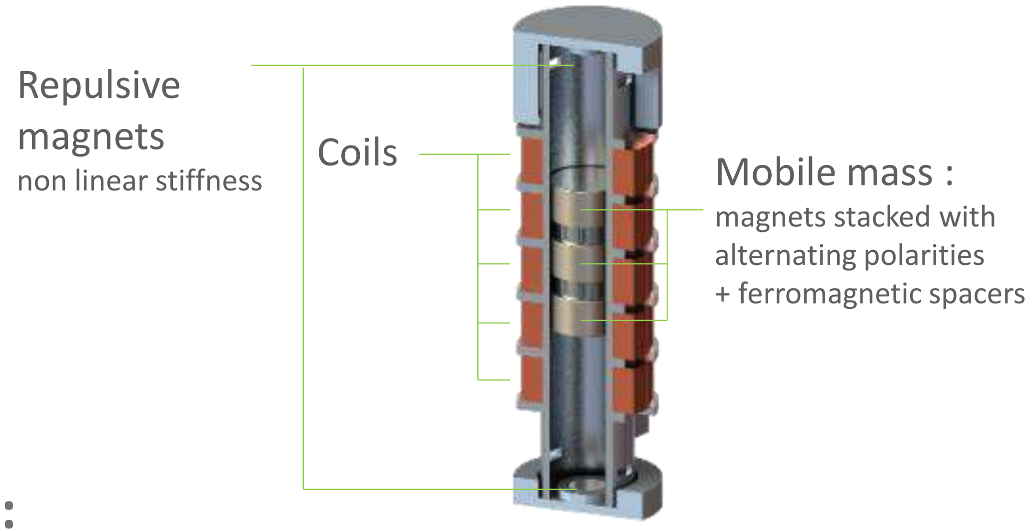
- Power densities in practice …

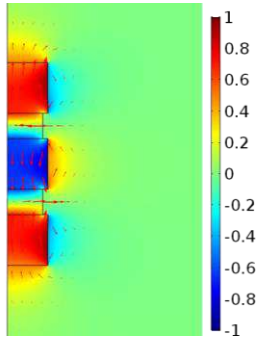


# Vibration Energy Harvesting : CEA examples

- **Wireless Body Area Networks (WBAN) applications : autonomous wearable sensors**
  - **Electromagnetic** non-linear resonant system optimised for the **very low frequencies** (<30Hz)
  - ”**AA-battery size**” (9cm$^3$) with a mobile mass (magnets) of 5.7g
  - Optimization method
    - Based on a set of experimental acceleration measurements
    - Joint optimization of the electromagnetic coupling + magnetic repulsion



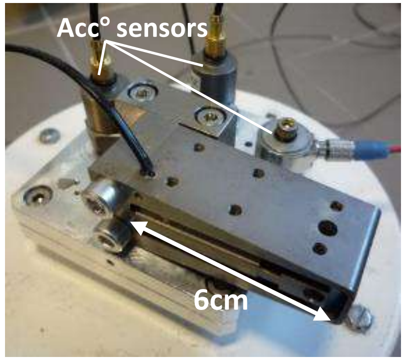

Simulation EF (COMSOL)


[M. Geisler et al., 2017]

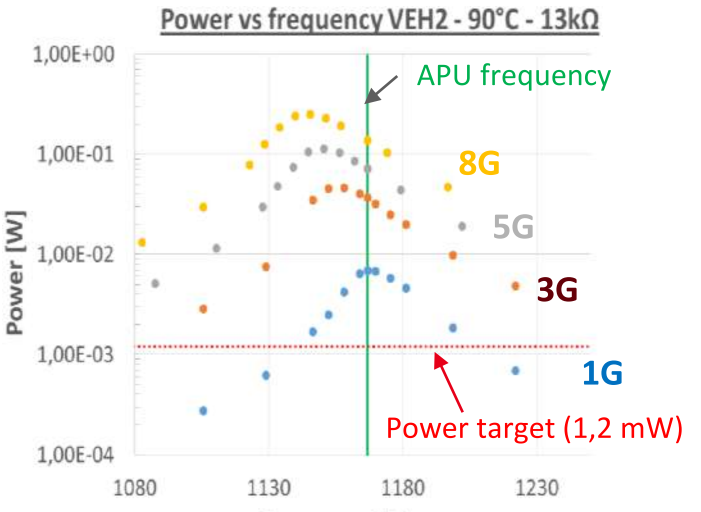
- **Results :**
  - Hand-shaking (6 Hz, 2g): 6,57mW
  - Upper arm : Run @ 6.4 km/h : 3.94mW, Run @ 8 km/h : 4.96mW
  - **550µW/cm$^3$**

# Vibration Energy Harvesting : CEA examples

- **Vibration energy harvesting for SHM in aeronautic environnements**
  - Piezoelectric cantilever structure (bimorph)
  - Analytical Modeling + Finite Elements (Comsol)
  - Dedicated power management circuit
  - Application : power supply of a conditioning circuit for 3 acceleration sensors
  - Constraints :
    - « High » frequency : 1167Hz
    - High acceleration range (8G → 20G)
    - Nominal operation @ 90°C, up to @ 120°C




Test bench and harvester (130g,30cm³)



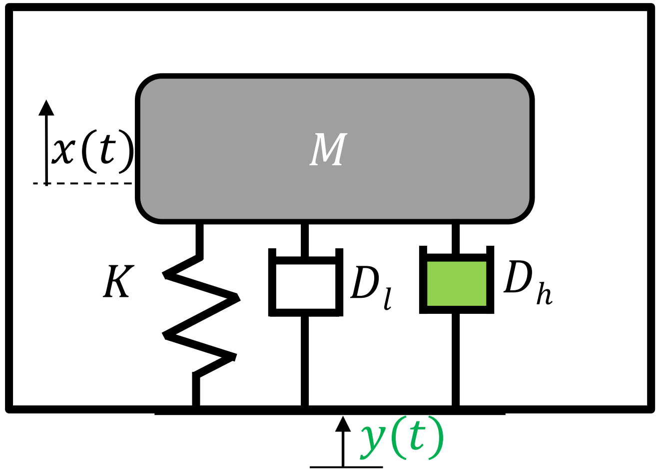

[Gasnier et al., 2018]

- **Results**
  - Experimentally validated in climatic chamber (**8G-20G @90°C et 120°C**), $10^7$ cycles
  - **Tested in real conditions** : SAFRAN's APU (13G-15G / 70°C)
  - Maximum output power measured : **200mW@ 8G - 1167Hz**

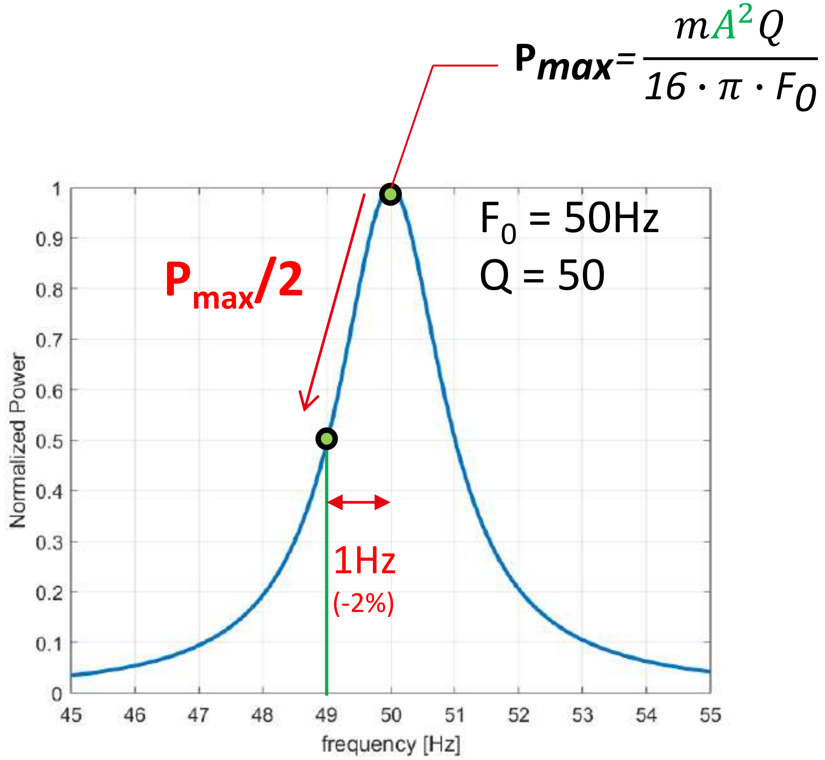
APU SAFRAN

# Vibration Energy Harvesting : challenges

- **Vibration Energy Harvesters are very selectives**




Modèle mécanique simplifié d'un récupérateur d'énergie vibratoire

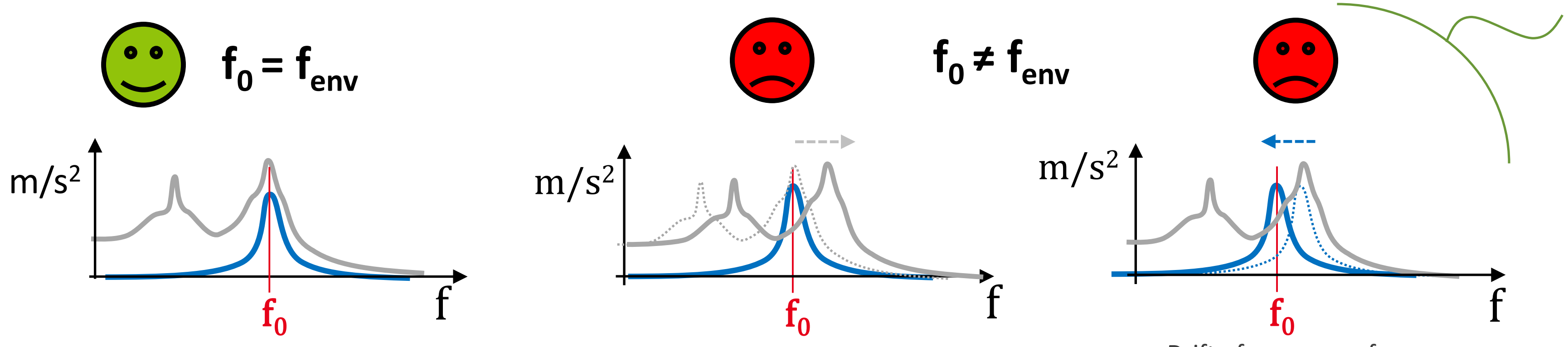



→ VEHs are « environnement specifics » (frequency, Amplitude)

→ Frequency selectivity has detrimental consequences on their functional reliability

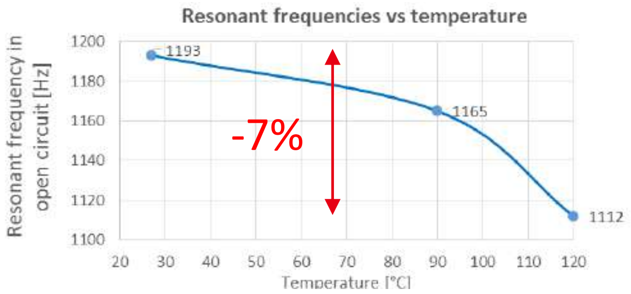
# Vibration Energy Harvesting : challenges

- **Harvester's resonance frequency vs environnement's frequency**




Frequency variation of the environment

Drift of resonance freq. (T°, ageing, …)




**CEA prototype / SAFRAN**

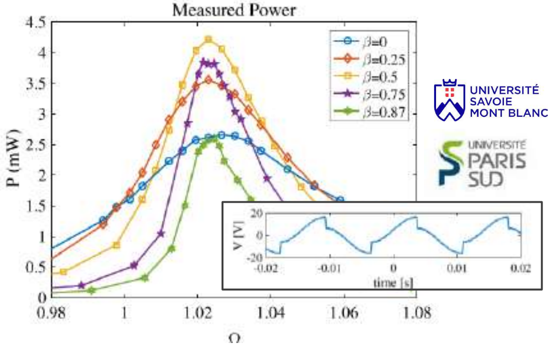
→ Need to dynamically tune the harvester to compensate for thermal drifts and ageing

**Target ⇨ Bandwidth (BW) > 10-20% $f_{res}$**

- **Different approaches to counter frequency selectivity**
  - Multi-beam
  - Frequency-up conversion
  - Non-linear oscillators
  - **Electrical frequency tuning**

UNIVERSITÉ SAVOIE MONT BLANC

[Badel *et al.*, 2014]



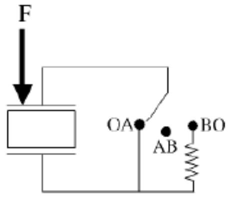

UNIVERSITÉ SAVOIE MONT BLANC

UNIVERSITÉ PARIS SUD

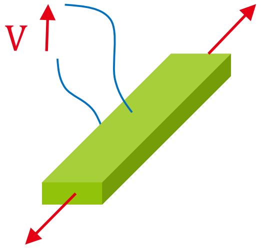
[Lefeuvre *et al.*, 2017]

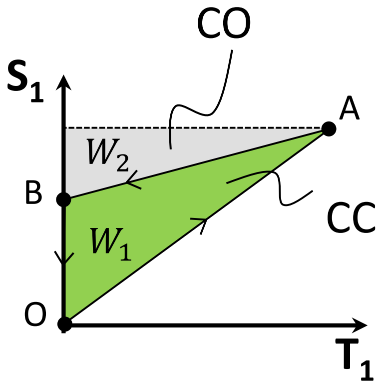
# Vibration Energy Harvesting : challenges

- **The coupling : static case**
  - The material coupling




[ANSI IEEE]

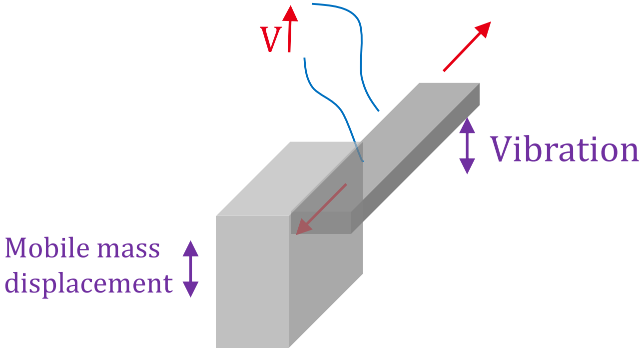



$$k_{31}^2 = \frac{W_{elec}}{W_{elastic\_piezo} + W_{elec}} = \frac{W_1}{W_1 + W_2}$$

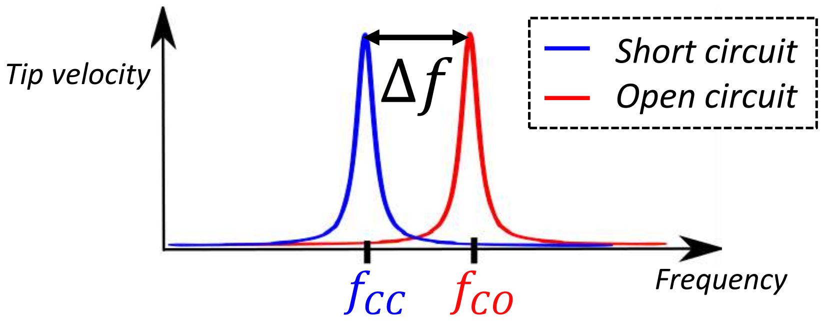
$$k_{31}^2 = \frac{s_{11}^E - s_{11}^D}{s_{11}^E}$$

  - The global electromechanical coupling




$$k^2 = \frac{W_{elec}}{W_{total}} \propto \frac{W_{elec}}{W_{useful\_tot\_Piezo}} \times \frac{W_{useful\_tot\_Piezo}}{W_{total}}$$

$$\boldsymbol{k^2 = \frac{f_{co}^2 - f_{cc}^2}{f_{co}^2}}$$




→ **The higher $k^2$, more the impact on the stiffness (thus the resonance freq.) and the damping is important**

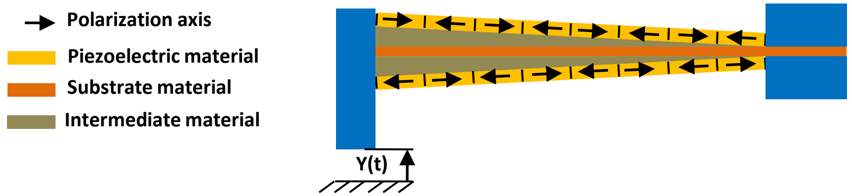
→ **Design and fabrication of strongly coupled cantilevers (high $k^2$)**

# Vibration Energy Harvesting : challenges

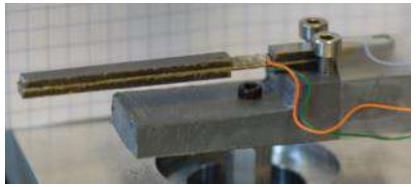
- **Goal : increase the global electromechanical coupling**
  - By using intrinsically **highly coupled materials**
    - High $k^2$ : very large bandwidth (BW)

    High BW but stronlgly coupled materials (single-crystal) = poor temperature resistance
  - By designing **structures** that
    - … **localize** the elastic energy in the piezo material
    - … **homogenize** the deformation in the piezo material

    High BW but complex structures : fabrication cost, limited robustness, low quality factors …




BW : 38%



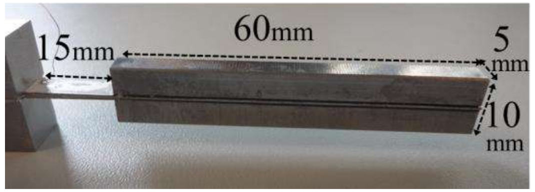
[Badel and Lefeuvre, 2014]

BW : 32%

[Ahmed-Seddik et al., 2012]

- **Phd-thesis CEA-USMB (D. Gibus)**
  - Study, modeling and caracterization of strongly-coupled structures adapted to industrial environnement
    - Easy to fabricate (cost, robustness)
    - Ceramic-based cantilevers operating @ high temperature

      ex : PZT-5A ($k_{31}^2 = 15\%, T_c = 360°C$)




[Gibus et al., 2019]

# Vibration Energy Harvesting : challenges

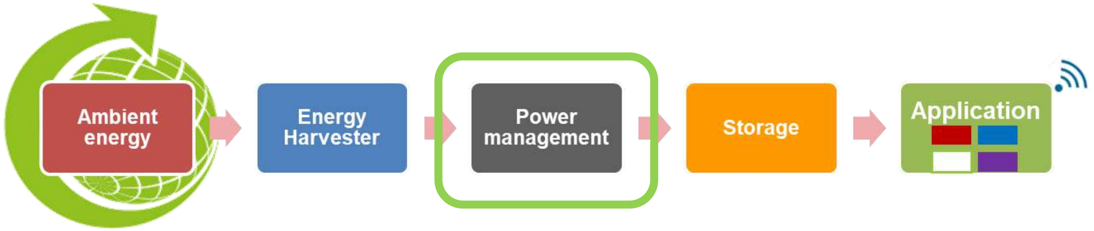
- **Results**
  - Exploiting the ‘**long tip mass**’ (high rotary inertia) and **plane strain** configurations

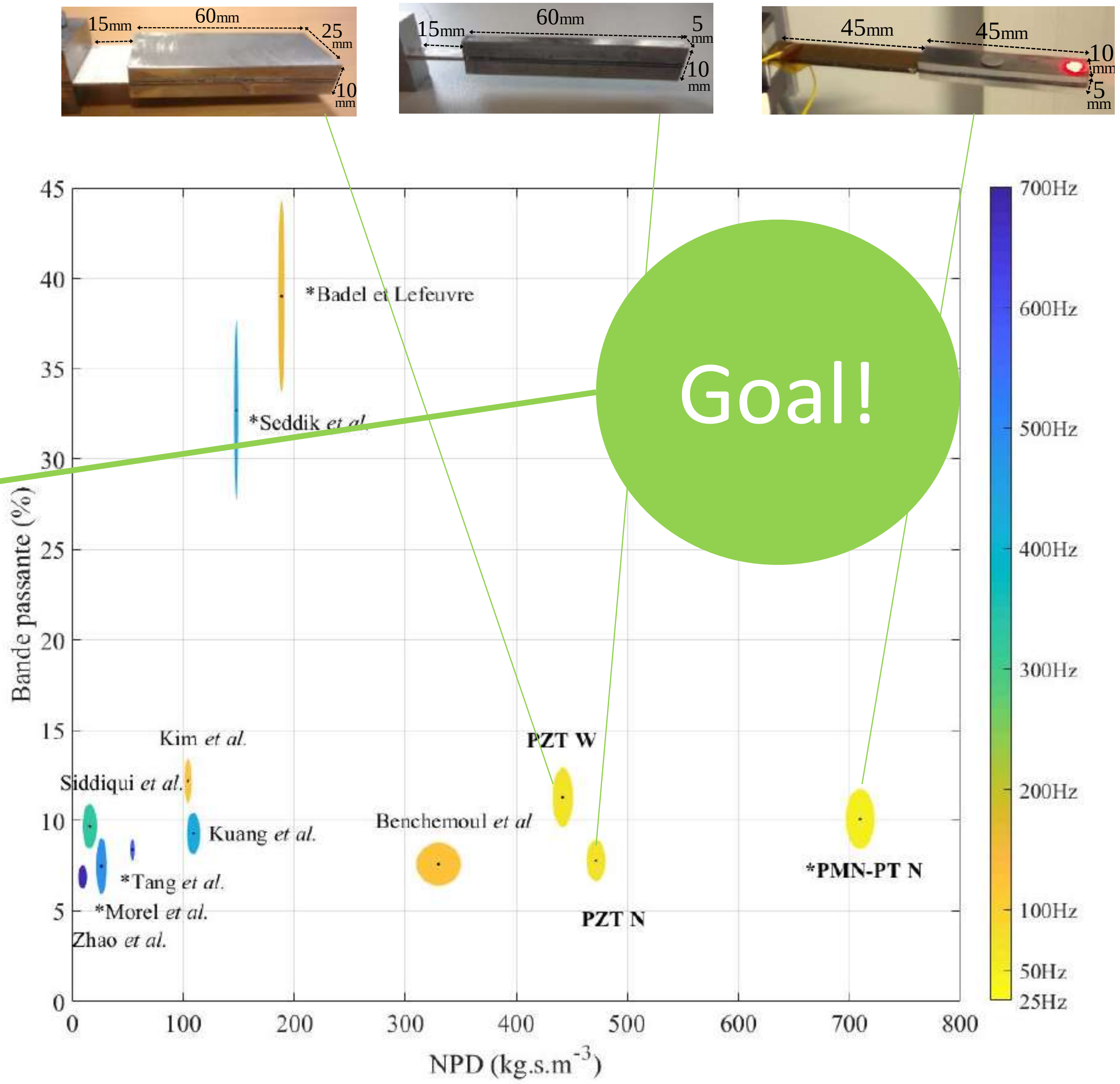
  → High couplings with ceramic-based stuctures ($k^2$>10%) : **Bandwidths : 8% to 12%** of the central frequency

  → Very **good power densities** (400 to 700 kg.s.m$^{-3}$)

- **Perspectives :**
  - High power densities and Bandwidth
  - Size reduction
  - Robustness et ageing

- Need for intelligent **power management circuits** able to **dynamically** tune the harvester ’s behavior as a fonction of the input frequency



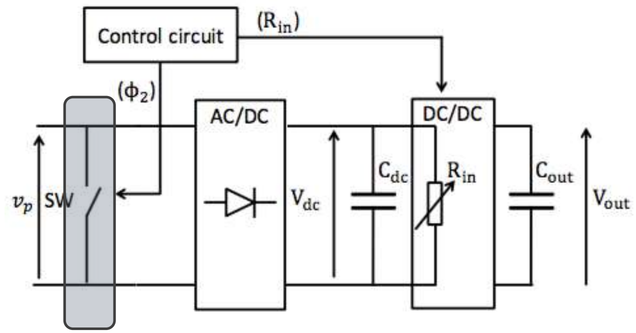




[David Gibus Phd, 2020]

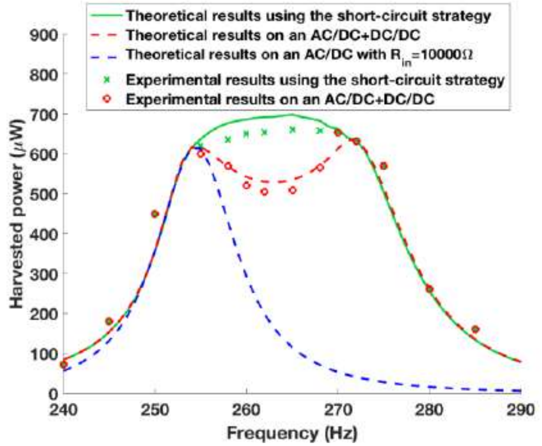
# Vibration Energy Harvesting : Pmngt circuits



- **Non-linear extraction strategies for strongly-coupled devices : Phd-thesis CEA-USMB (A. Morel)**
  - SC-SECE technique : emulation of a capacitive behavior between $f_{cc}$ and $f_{sc}$
  - results : 600µW over a 20Hz bandwidth

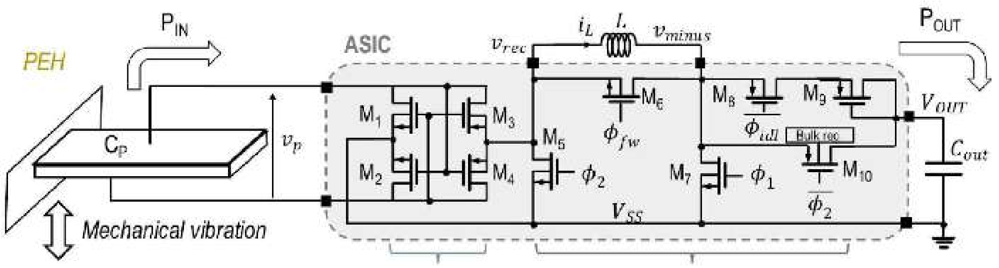


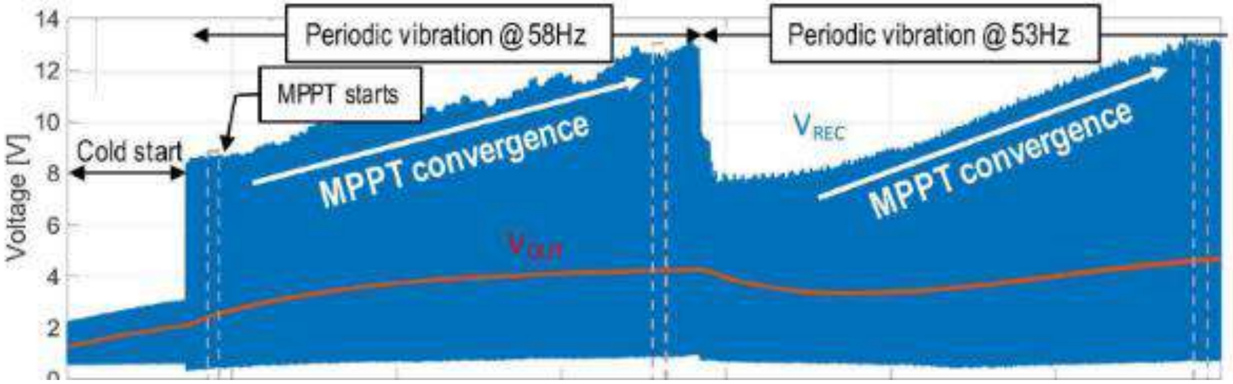

[A. Morel et al., 2016]




→ No need of a large off-chip capacitive bank for the frequency tuning

- **ASICs performing automatic frequency tuning to optimize the energy extraction**




[Morel *et al.*, ISSCC 2020]

# Outline

Introduction : Energy Harvesting, dream and reality

1 Quantitative/qualitative aspects, system view and challenges

2 Mechanical Energy Harvesters
( + power management circuits)

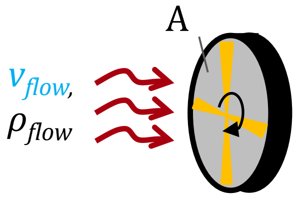
3 Flow-driven Energy harvesters

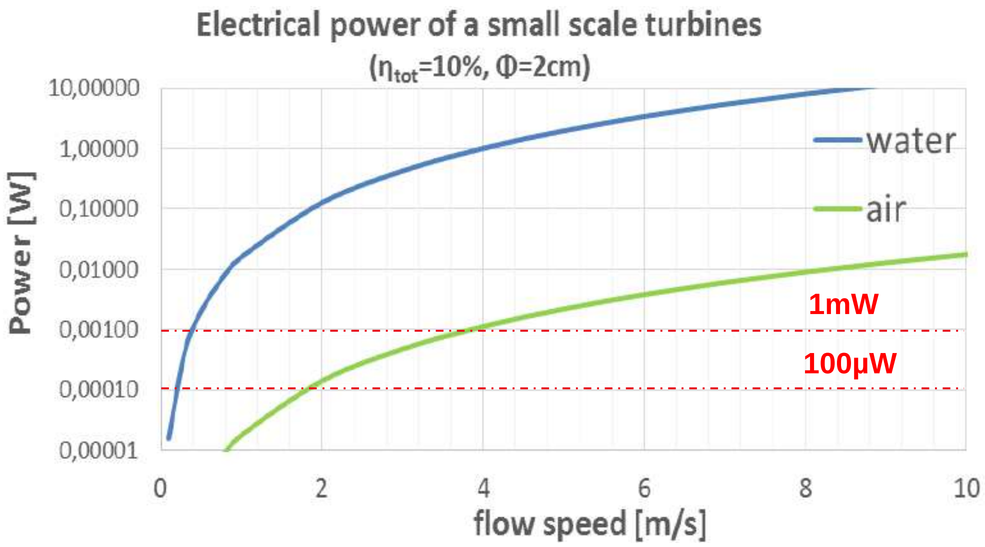
Conclusion

# Fluid Flow energy harvesting : principle

- **Power extractable from flows :**

$$P_{elec}[W] = \frac{1}{2} \cdot \eta_{tot} \cdot \rho_{flow} \cdot A \cdot v_{flow}^{3}$$

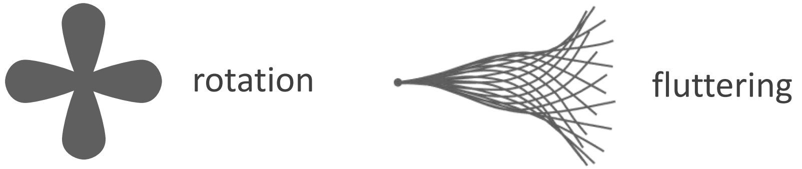


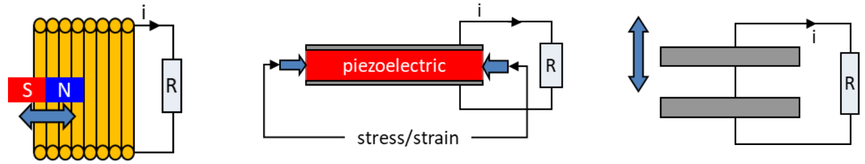

- **Small size : expected efficiency and power :**
  - $\eta_{tot}$ < 0,59 (Betz's law)
  - 0,3 < $\eta_{tot}$ < 0,4 for typical windmills
  - $\eta_{tot}$ < 0,2 for small scale devices

  → Flow driven energy harvesters enable to supply WSN from a few m/s

- **Main types of flow-to-mechanical conversion :**



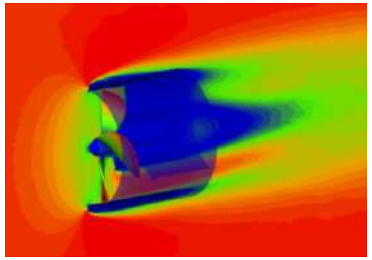

- **Various types of mechanical-to-electrical converters :**



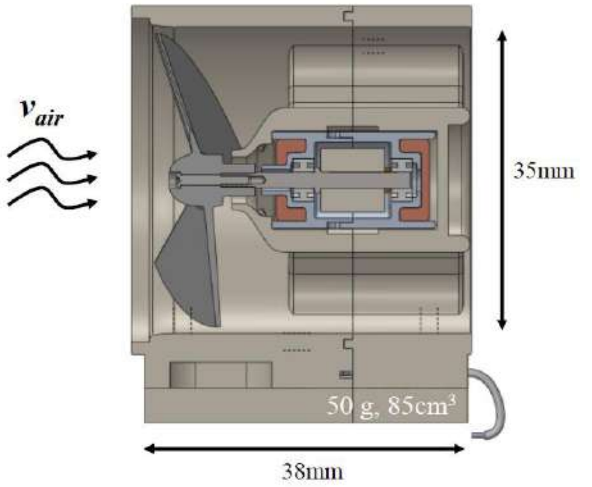

**→ Flow driven harvesters are less dependents to environmental conditions (no freq. component)**

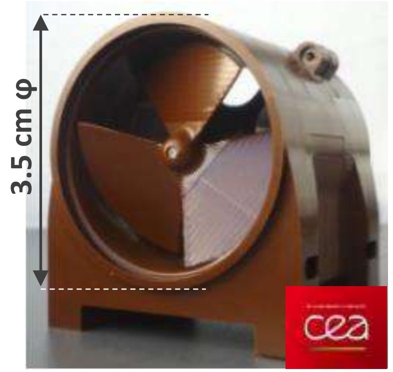
# Airflow energy harvesting : CEA prototypes

- **Air flow energy harvesting thanks to µ-turbines (miniature turbines)**
  - Typical applications : harsh and HVAC applications
  - Coreless Permanent magnet generator (no cogging issues) (rotating permanent magnet surrounded by a fixed coil)
  - Experimental results :
    - Cuttin speeds (2 m/s to 5 m/s)
    - Electrical Powers : 200 µW @1.5 m/s - 3.7 mW @ 3 m/s
    - End-to-end efficiency : 20.1% @ 2 m/s, 23.9% @ 3 m/s



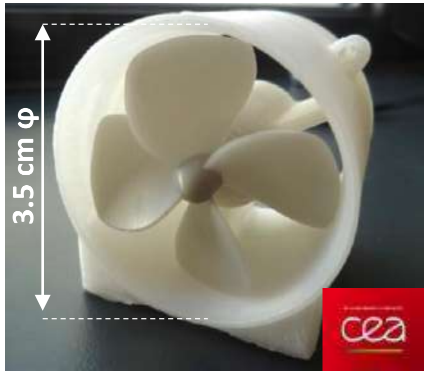
CFD solver (Altair AcuSolve)



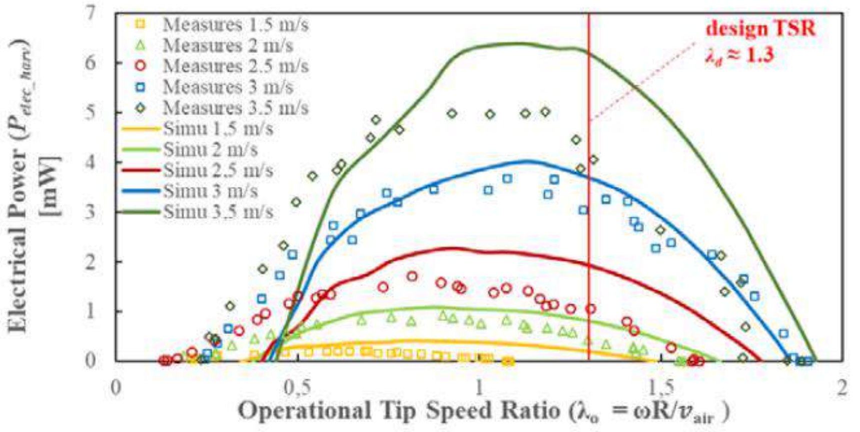




250°C compliant µturbine for aeronautic env.

[PowerMems 2018]

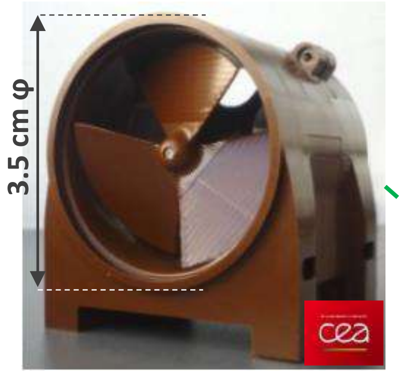



3D printed µturbine for HVAC applications

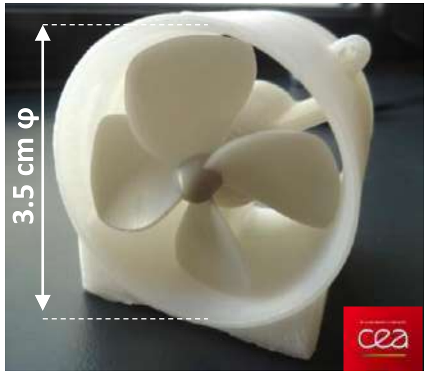


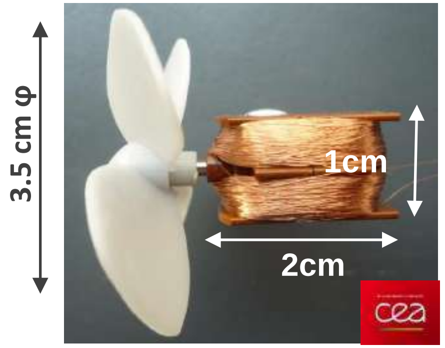

[PowerMems 2019]

[PowerMems 2018]



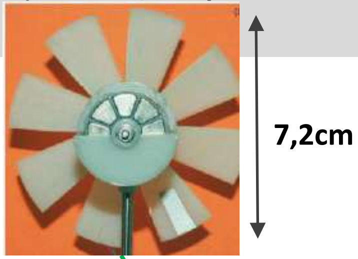

[PowerMems 2019]



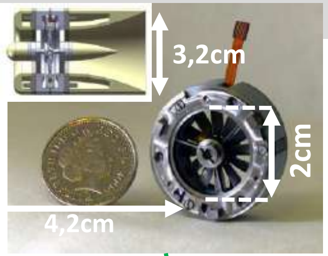

[Marin et al., 2015]

2,58mW @ 2m/s



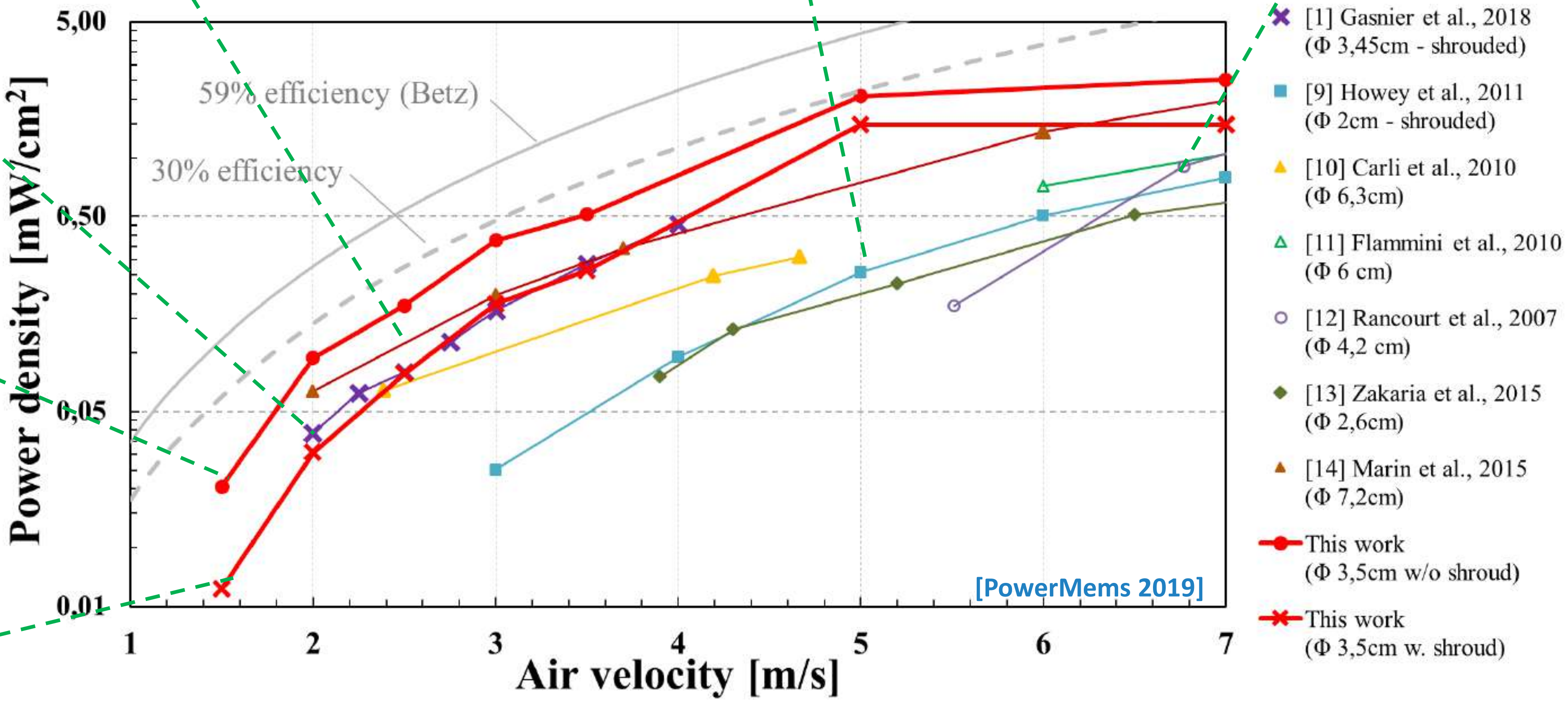

[Howey et al. 2011]

0,08µW @ 3m/s



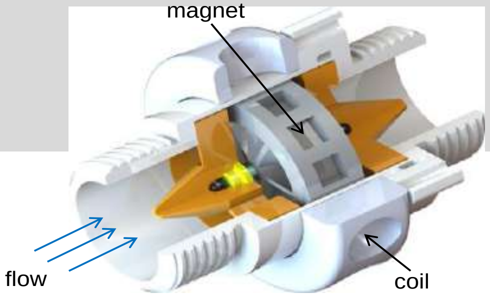

[Rancourt et al., 2007]

2,4mW @ 5,5m/s

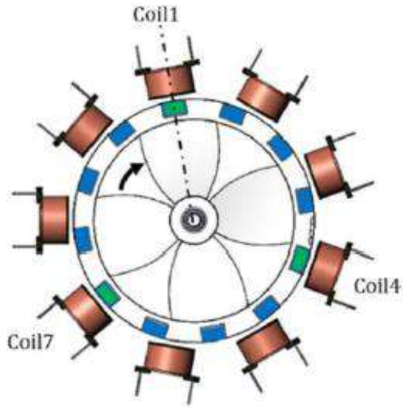



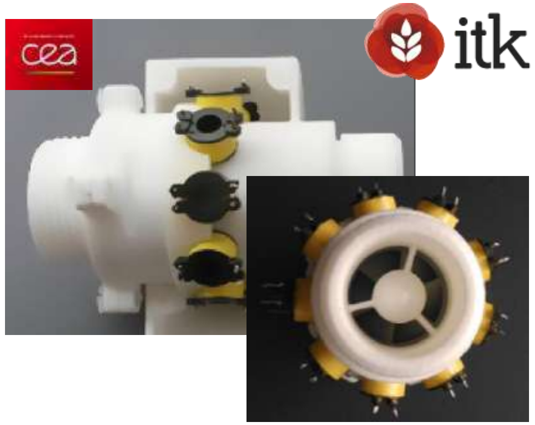

→ µturbines operating from 2 m/s and having power densities from **50-100µW/cm² @ 2m/s** to **250-500µW/cm² @ 3,5m/s**

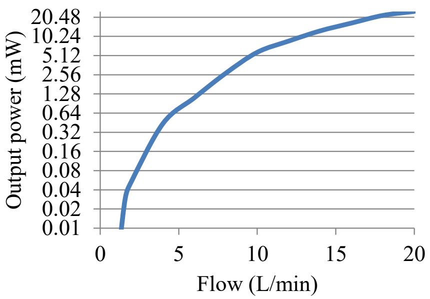
# Waterflow energy harvesting : CEA prototypes




- **Water flow energy harvesting with electromagnetic converters**
  - Typical applications : district heating / cooling, culture monitoring / irrigation
  - Coreless Permanent magnet generator (no cogging issues)
  - Distributed magnets at the periphery of the turbine with alternate polarities
  - Experimental results :
    - Open-circuit voltages ≈ 4V @ 10L/min - 8V @ 20L/min
    - Electrical powers ≈ **7,5mW @ 10L/min – 32mW @ 20L/min**
    - $\Delta p$ = **0,05 bars@30L/min** (coils short-circuited), minor loss coef of 3,94



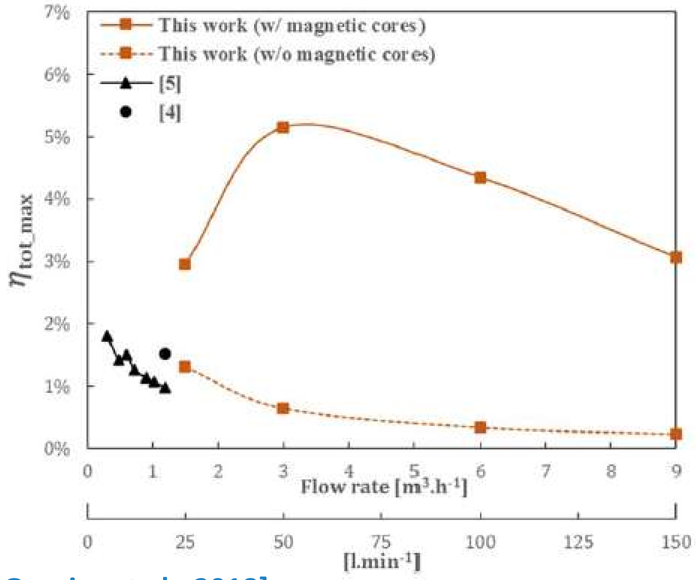






[S. Boisseau et al., 2016]

First generation, DN20

second generation, DN40




[P. Gasnier et al., 2018]

# Outline

Introduction : Energy Harvesting, dream and reality

1 Quantitative/qualitative aspects, system view and challenges

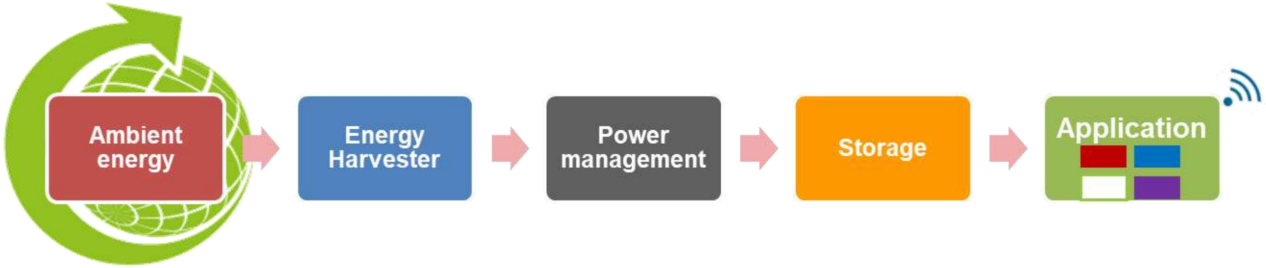
2 Mechanical Energy Harvesters
(+ power management circuits)

3 Flow-driven Energy harvesters

**Conclusion**

# Conclusion

- **Energy harvesting technologies for small systems :**
  - Still for **specific** applications and particular environments
    - where batteries cannot operate (high T° par ex.)
    - Isolated environments
  - But … *mainstream* applications are increasing
    → 3 industrializations in progress at CEA (sport, domotic, connected irrigation)
  - A study of the **whole system** is needed
    → "**A**dequation **H**arvester – **C**ircuit"

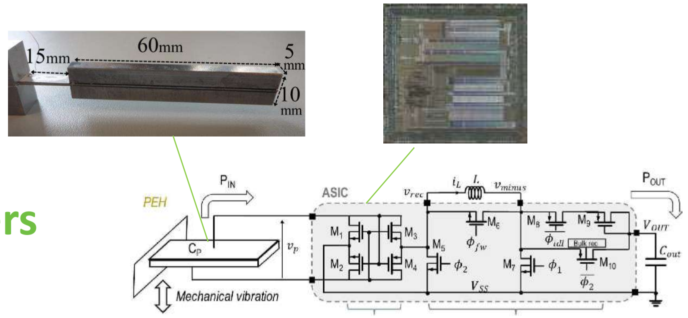



  - The paradigm of "**sensors dissemination**" should not make us forget the environmental impact and the cost of the technologies it promotes

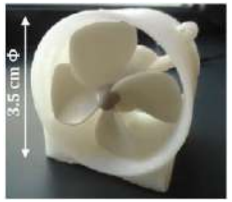
# Conclusion

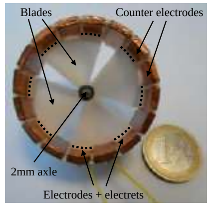
- **Mechanical Energy Harvesting : towards democratization and industrialization**
  - Cost
  - Reliability
    → Robustness and ageing
    → functional reliability

- **Vibration Energy Harvesting :**
  - Good power densities (>10mW/cm$^3$.g$^2$) but very selective
    **→ Countering frequency selectivity through strongly coupled piezo harvesters combined with self-adaptive power management circuits**




- **Flow Energy harvesting :**
  - High power, no frequency dependence
    **→ Decrease in dimensions**
    **→ Towards wider operating ranges**
    **→ Decrease in pressure losses**

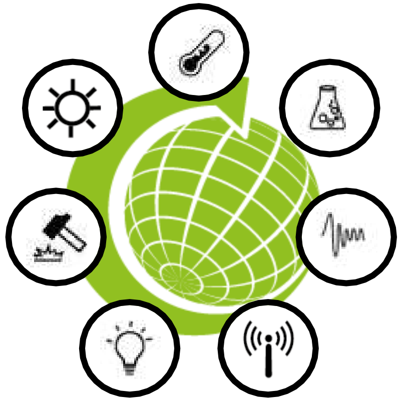


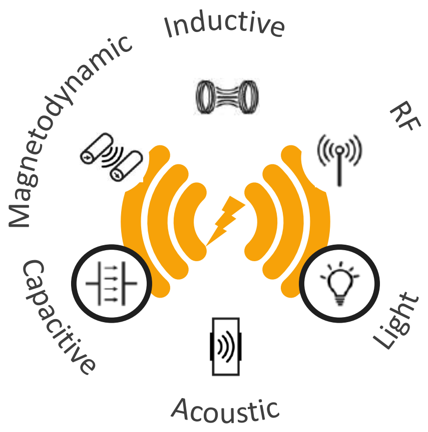

## Energy harvesting to power WSN … not only …

**Wireless Power Transfer**

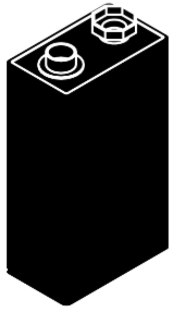
Energy Harvesting technologies



Wireless Power Transfer technologies



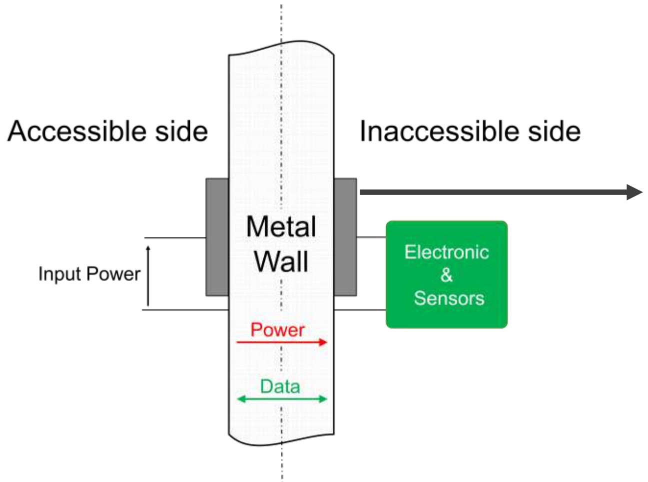

**VS**



# Wireless Power Transfer Technologies Developed at CEA

## Acoustic WPT

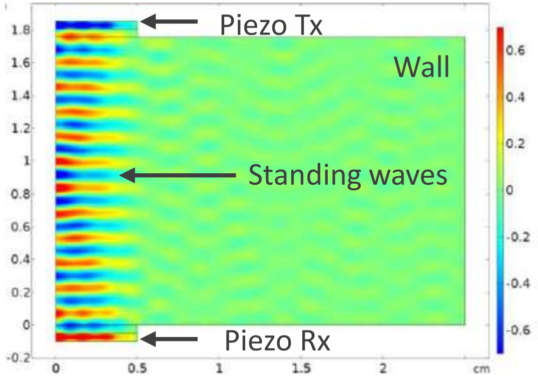
- Power transfer through metal using 2 piezoelectric transducers
- **High power with high efficiency**



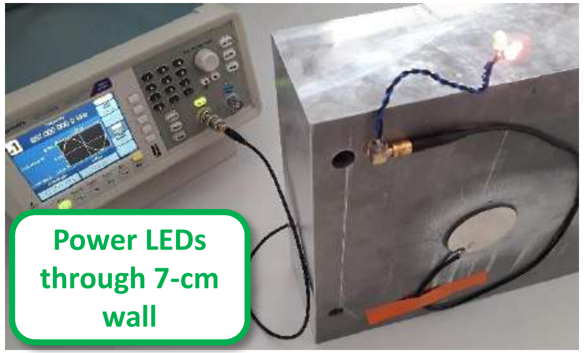


**10 W (50 % eff.) through 55-mm-thick steel wall at 500 kHz**

Finite element simulation



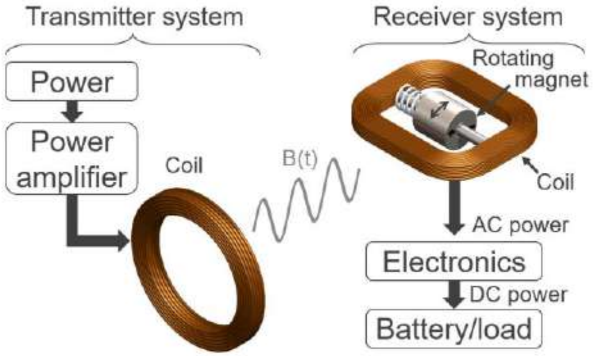

Acoustic WPT demo through thick wall



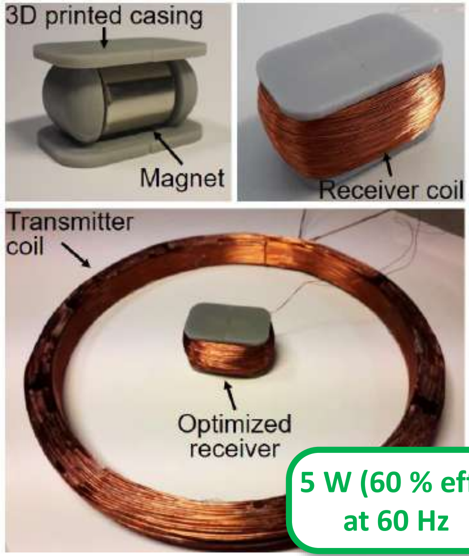
**Power LEDs through 7-cm wall**

## Magnetodynamic WPT

- Power transfer at **low frequency** using a moving magnet embedded in the receiver coil

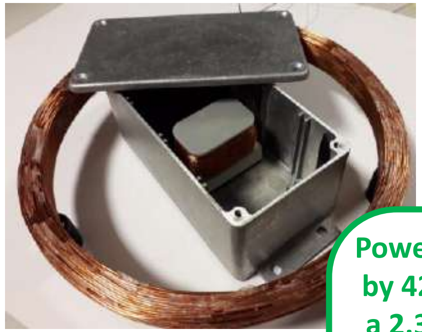



Safe transmission possible through :

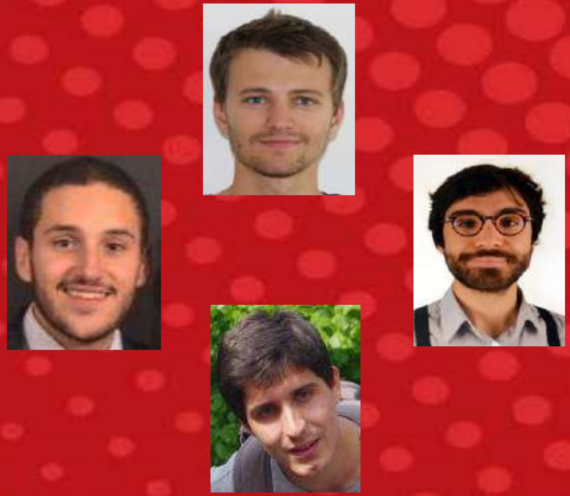

**5 W (60 % eff.) at 60 Hz**

Magnetodynamic WPT demo through metal



**Power decreases by 42% through a 2.3-mm-thick Aluminum box, but it works!**

# Merci à l'équipe récupération d'énergie actuelle



*les (valeureux) doctorants*

## et merci de votre attention

# Some references :


**[B. Ahmed-Seddik thesis., 2012]** : “Systèmes de récupération d'énergie vibratoire large bande », thesis, Grenoble University, 2012

**[T. Ricart et al., 2012]** : “Macro energy harvester based on Aluminium Nitride thin films,” in 2011 IEEE International Ultrasonics Symposium, 2011, pp. 1928–1931.,

**[G. Despesse et al., 2007]** : “Fabrication and characterization of high damping electrostatic micro devices for vibration energy scavenging,” Proc Des. Test Integr. Packag. MEMS MOEMS, pp. 386–390, Jun. 2005

**[S. Boisseau et al., 2011]** : “Cantilever-based electret energy harvesters,” Smart Mater. Struct., vol. 20, no. 10, p. 105013, 2011.

**[M. Geisler et al., 2017]** : “Human-motion energy harvester for autonomous body area sensors,” Smart Mater. Struct., vol. 26, no. 3, p. 035028, 2017.

**[S. J. Roundy et al., 2003]** : “Energy Scavenging for Wireless Sensor Nodes with a Focus on Vibration to Electricity Conversion,” University of California, Berkeley), 2003.

**[Morel et al., 2016]** : “Active AC/DC control for wideband piezoelectric energy harvesting,” J. Phys. Conf. Ser., vol. 773, no. 1, p. 012059, 2016.

**[Elfrink et al., 2009]** : “First autonomous wireless sensor node powered by a vacuum-packaged piezoelectric MEMS energy harvester,” in 2009 IEEE International Electron Devices Meeting (IEDM), 2009, pp. 1–4

**[B. Ahmed-Seddik., 2012]** : “Self-powered resonant frequency tuning for Piezoelectric Vibration Energy Harvesters,” J. Phys. Conf. Ser., vol. 476, no. 1, p. 012069, 2013.

**[Badel et al., 2014]** : “Integrated bistable generator for wideband energy harvesting with optimized synchronous electric charge extraction circuit,” J. Phys. Conf. Ser., vol. 476, no. 1, p. 012107, 2013

**[Lefeuvre et al., 2005]** : “ Piezoelectric Energy Harvesting Device Optimization by Synchronous Electric Charge Extraction,” J. Intell. Mater. Syst. Struct., vol. 16, no. 10, pp. 865–876, Oct. 2005.

**[Lefeuvre et al., 2017]** : “Analysis of piezoelectric energy harvesting system with tunable SECE interface,” Smart Mater. Struct., vol. 26, no. 3, p. 035065, 2017

**[S. Boisseau et al., 2016]** : “Water flow energy harvesters for autonomous flowmeters,” J. Phys. Conf. Ser., vol. 773, no. 1, p. 012019, 2016

**[Howey et al. 2011]** : “Design and performance of a centimetre-scale shrouded wind turbine for energy harvesting,” Smart Mater. Struct., vol. 20, no. 8, p. 085021, 2011.

**[Rancourt et al., 2007]** : “Evaluation of Centimeter-Scale Micro Wind Mills: Aerodynamics and Electromagnetic Power Generation,” PowerMems, 2007.

**[Marin et al., 2015]** : “Micro Wind Turbine for Powering Wireless Sensor Nodes,” Energy Harvest. Syst., vol. 3, no. 2, pp. 139–152, 2015.

**[M. Perez et al., 2015]** : “An electret-based aeroelastic flutter energy harvester,” Smart Mater. Struct., vol. 24, no. 3, p. 035004, 2015.

**[M. Perez et al., 2016]** : “A cm scale electret-based electrostatic wind turbine for low-speed energy harvesting applications,” Smart Mater. Struct., vol. 25, no. 4, p. 045015, 2016.

**[S. Boisseau et al., 2013]** : “ Self-starting power management circuits for piezoelectric and electret-based electrostatic mechanical energy harvesters,” J. Phys. Conf. Ser., vol. 476, no. 1, p. 012080, 2013

**[P. Gasnier et al., 2014]** : “An Autonomous Piezoelectric Energy Harvesting IC Based on a Synchronous Multi-Shot Technique,” IEEE J. Solid-State Circuits, vol. 49, no. 7, pp. 1561–1570, Jul. 2014.

**[T. Chailloux et al., 2016 ]** : "Energy Harvesting from a Microbial Fuel Cell in Aquatic Environment using Off-the-shelf Components," Journal of Energy Harvesting and System, Walter De Gruyer, 2016

DE LA RECHERCHE À L’INDUSTRIE