FROM RESEARCH TO INDUSTRY

► Energy Harvesting Systems at CEA : Mechanical energy harvesters, power management circuits & ultra-low power electronics

11/07/2019

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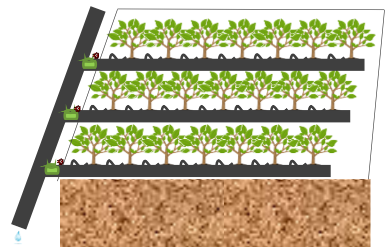
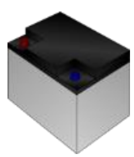
Autonomous communicating devices – System vision


IoT - ©nest

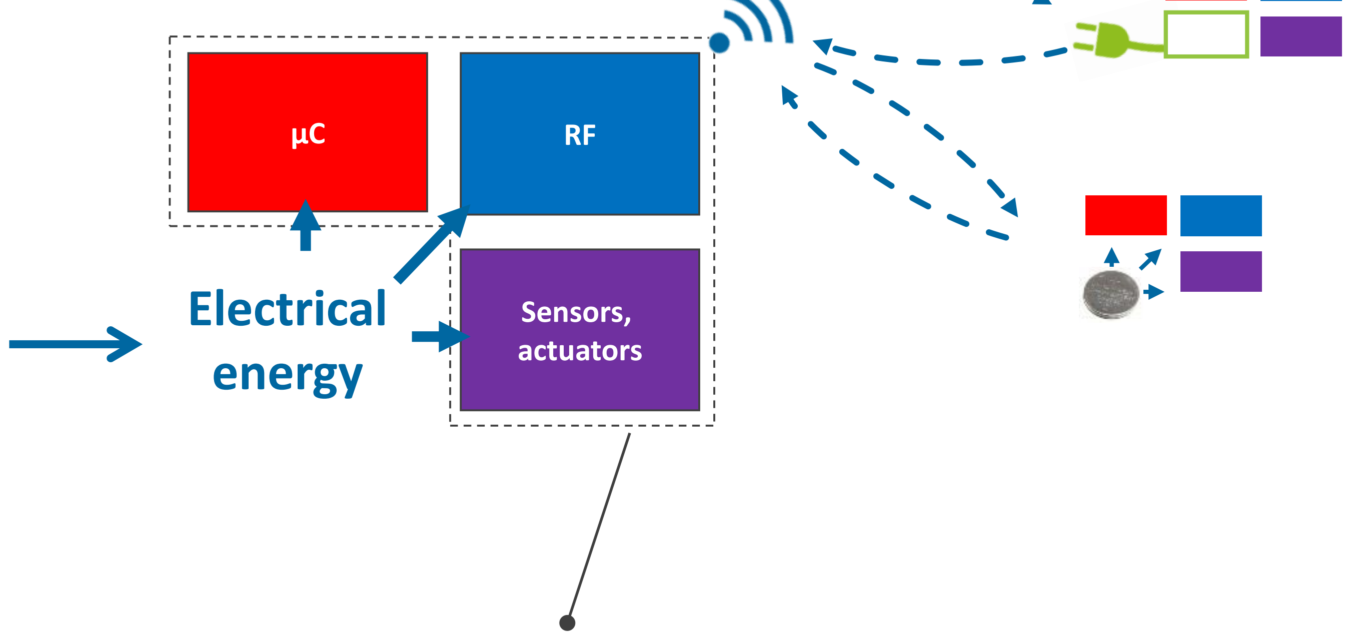

Harsh Environments


Abandoned Sensors

Primary cell



Rechargeable battery



"Autonomous" Wireless Communicating System

Autonomous communicating devices – System vision

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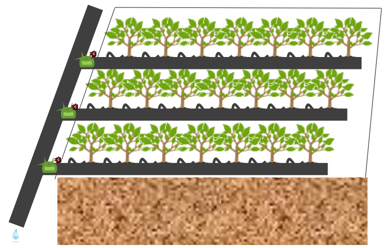
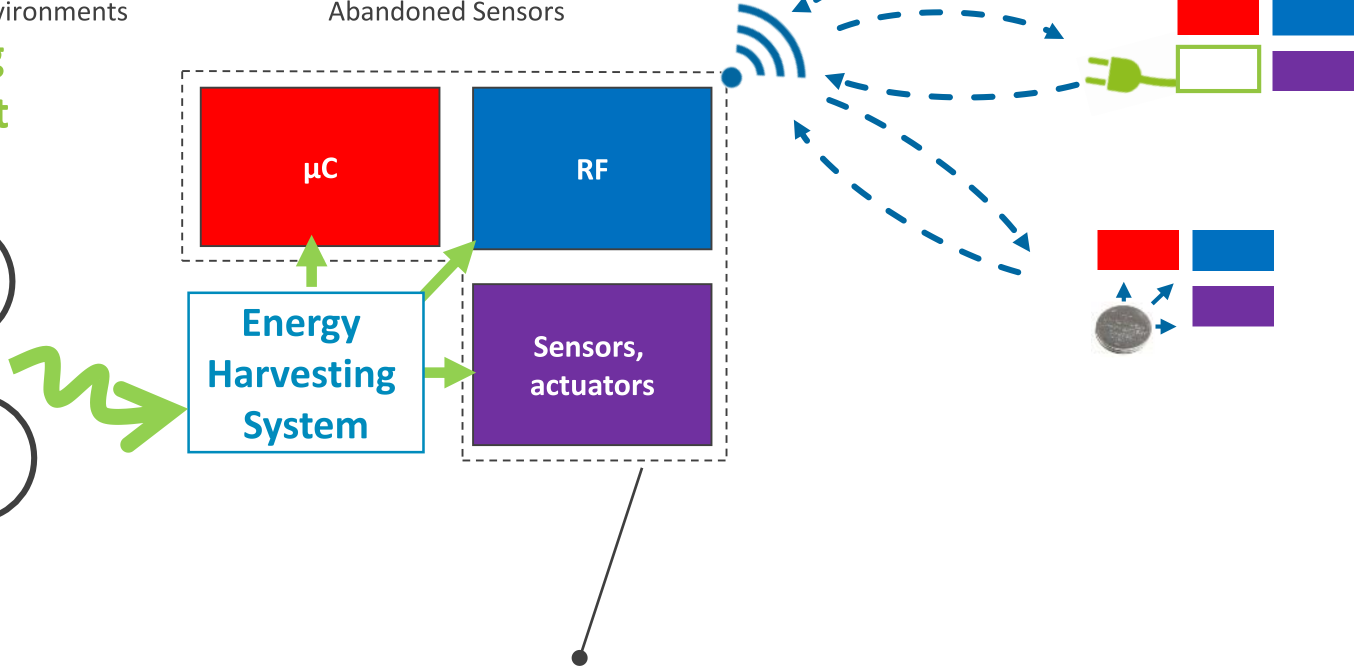
Harsh Environments



Abandoned Sensors

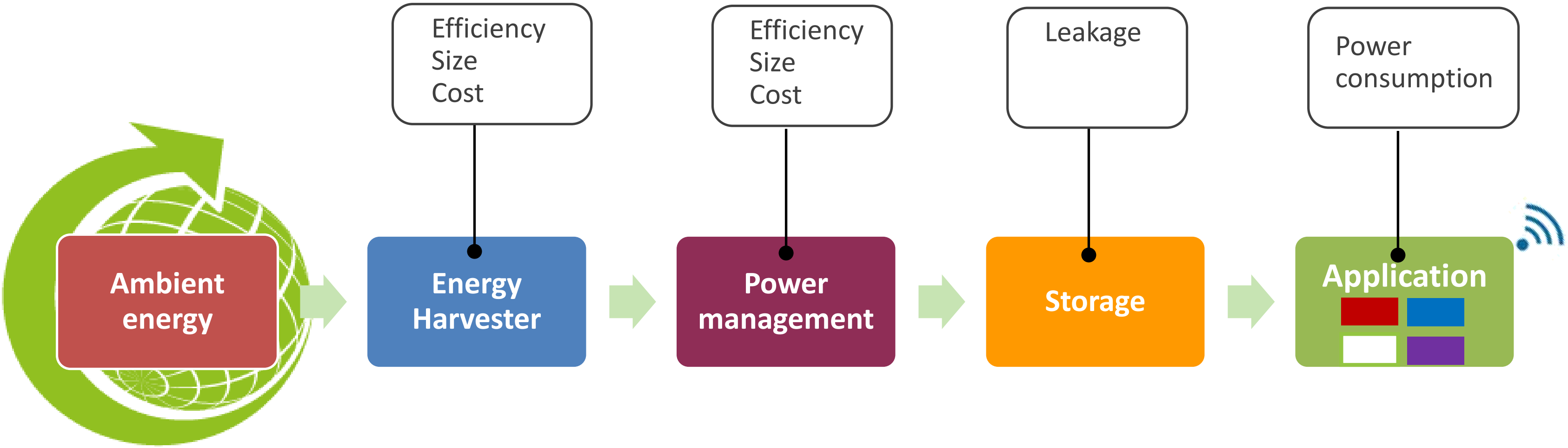
Energy source coming from the environment



Autonomous Wireless Communicating System

Energy harvesting for wireless sensor nodes

System vision : from ambient energy to autonomous devices

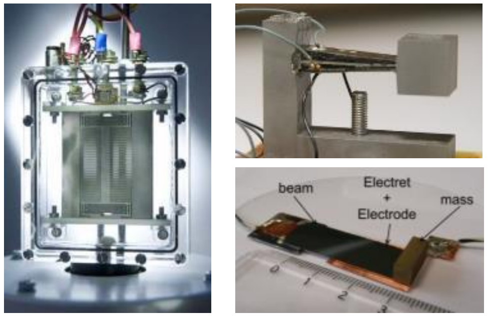


- Constraints & Optimizations on the whole energy harvesting chain

- Nowadays, the main challenges are :
  - The reliability of the harvesters (particularly for mechanical harvesters)
  - Their volumes (or power density) as compared with batteries
  - Their costs

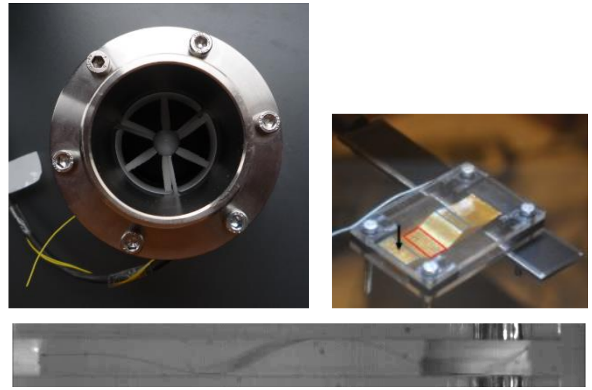
Energy Harvesting Overview

Energy Harvesters



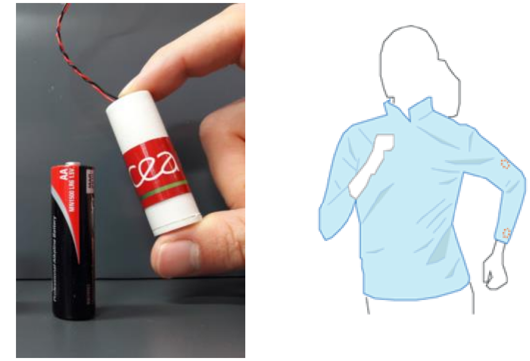
Vibration Energy Harvesters

⇒ Tuning of frequency/wideband devices
⇒ 1µW-10mW – some cm³
⇒ Industrial equipment, aeronautics



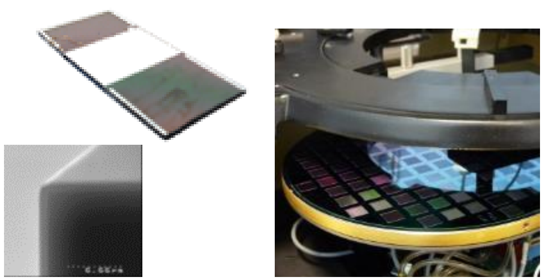
Airflow & Waterflow Energy Harvesters

⇒ µturbines & aeroelastic devices
⇒ 1mW-10mW – some cm³ – 2-3m/s
⇒ HVAC, industry, buildings
⇒ High Temp devices



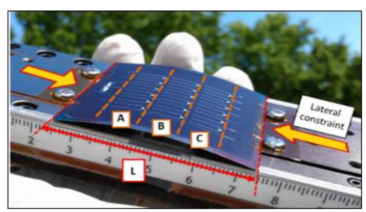
Low-frequency EH

⇒ Human movements
⇒ 1µW-5mW – some cm³
⇒ Wearables



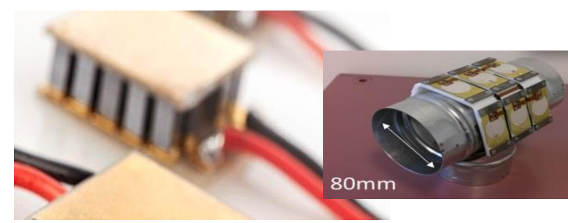
Smart Materials

⇒ Thin piezoelectric films (PZT, AlN)
⇒ Piezoelectric polymers (PVDF)
⇒ Magnets and thin magnetic films
⇒ Stable electrets



Photovoltaic cells

⇒ Conformable CIGS or amorphous Si, printed cells
⇒ Substrates : steel, titanium, thin glass (100 microns), plastics
⇒ Indoor: 0.01 – 0.1 mW/cm²
⇒ Outdoor:10 mW/cm²



Thermal Energy Harvesters

⇒ Thermoelectrical devices
⇒ Thermomechanical concepts
⇒ 3mW with ΔT°=10°C – some cm³
⇒ Sensors for industrial plant manufacturing

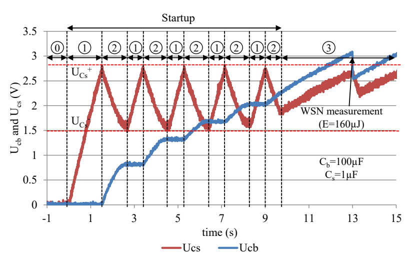
Power Management Circuits

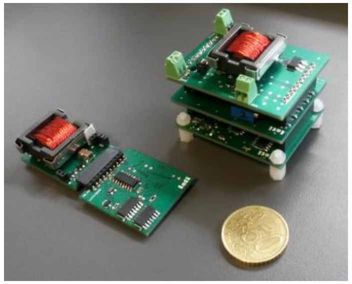
Turning Energy Harvesters into viable supply sources

- Making EH output usable by a Wireless System (3V-DC)
- Optimizing energy extraction & maximizing power conversion
- Battery-free or Battery-handling concepts

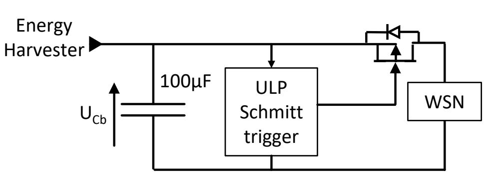
Discrete Power Management Circuits

⇒ Validate quickly the technical principles
⇒ Dedicated => higher performances than COTS
⇒ Active and passive circuits
⇒ Low-power consumption (<5µW)
⇒ **Supply a WSN down to 200nW harvested**





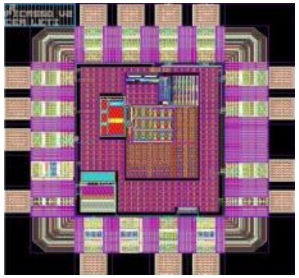
Battery-free PMC for vibration energy harvesters



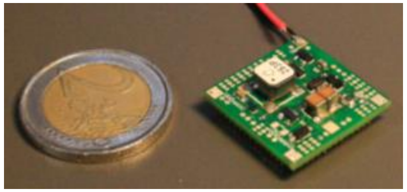
ULP schmitt trigger with a power consumption lower than a 10MΩ probe

ASICs

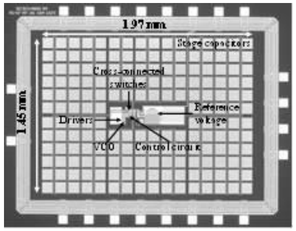
⇒ Reducing the size of the power management
⇒ Increase the capabilities (embedded intelligence)
⇒ Improve the performances



PV charger
95% efficiency
Low-cost (<50cents)



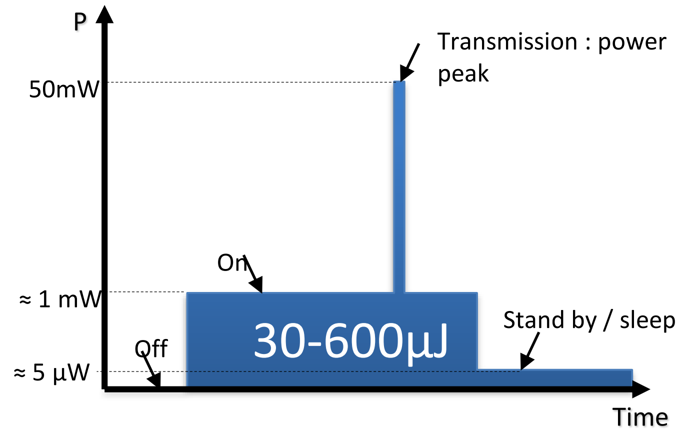
Hybrid approach: discrete + ASICs
mechanical energy harvesters
Efficiency >65%



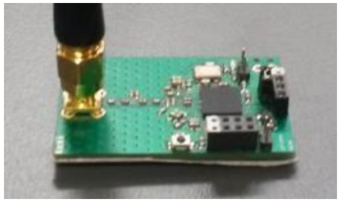
Fully integrated DC/DC converter for thermoelectric modules
Startup voltage: 250mV

Ultra-Low Power Electronics

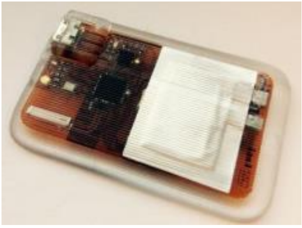
- **Developing ultra-low power systems**
  - 868MHz, Zigbee, Bluetooth nodes…
  - Optimizing the code and the microcontroller states to minimize its power consumption

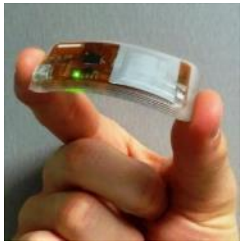


Low-power devices

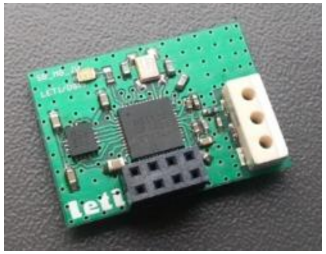


Generic 868MHz Low-power node - 30µJ /measure+emission



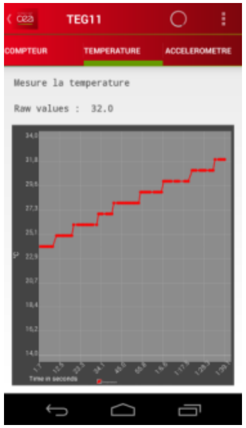


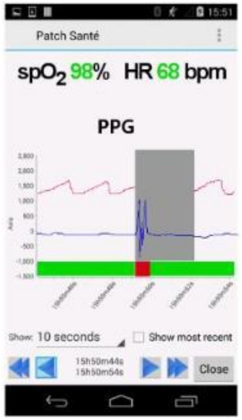
Low-power medical patches



Low-Power Bluetooth Low Energy & 868MHz Platforms 200µJ-600µJ / measure+emission

Environments for low-power devices





Apps for low-power sensor nodes

Proofs of Concept – Shock & Vibration Energy Harvesters

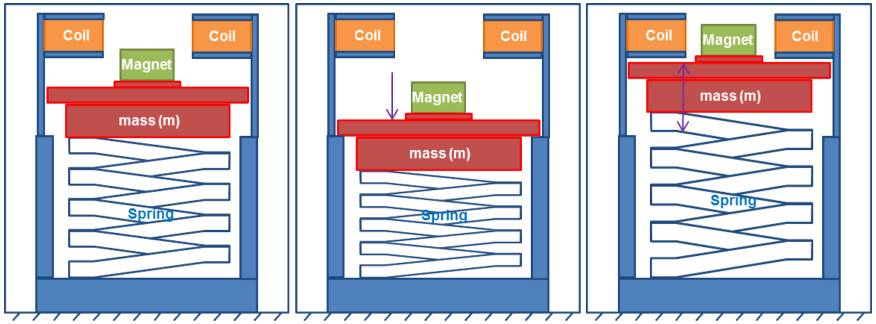
20 000 G Shock Energy Harvester

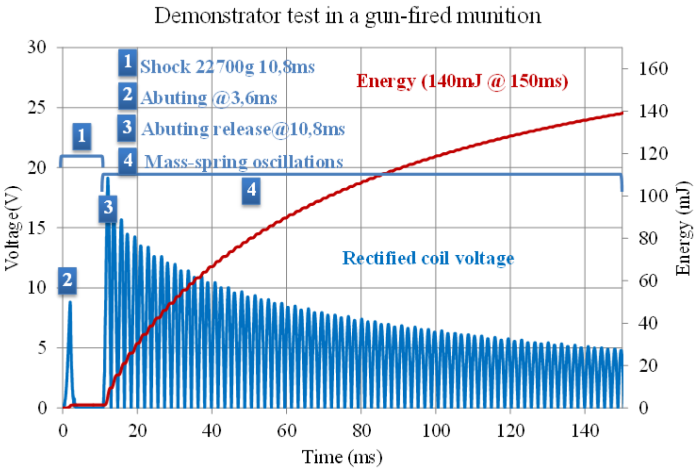
- **Shock Energy Harvesters for shells**
  - 20000G shock energy harvester
  - Energy required : 200mJ to 600mJ in 150ms
  - Lifetime >15-20 years → batteries

  - Concept
    - Energy storage in a mass-spring structure during the firing phase (20000G)
    - High G→compression of m-k → oscillations → electricity
    - Coil-magnet architecture to turn oscillations into electricity

  - Experimental results
    - 22700G shock
    - 140mJ generated in 150ms
    - 4,83W peak → 41mW/cm^3

  - First 20'000G shock energy harvester tested in a real environment

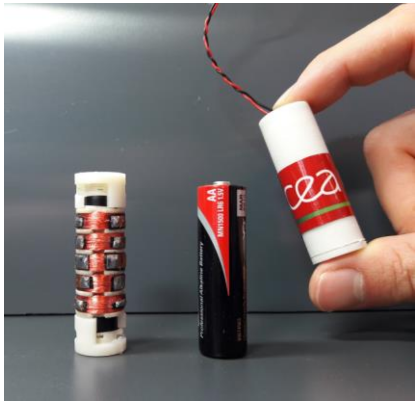


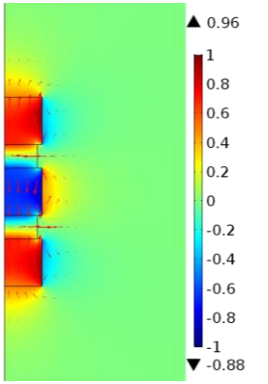


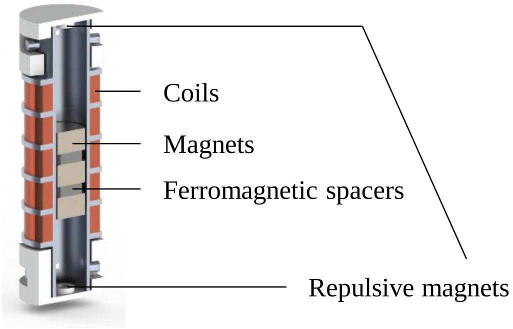
Low-Frequency Vibration Energy harvesters

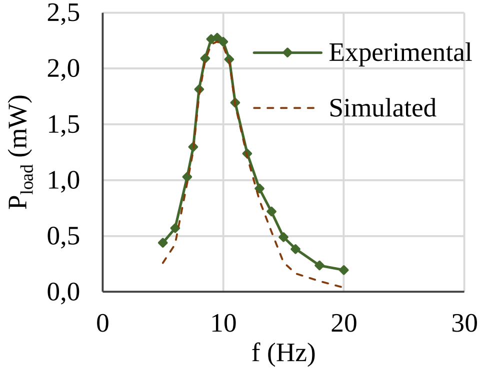
Power supply of wearable sensors

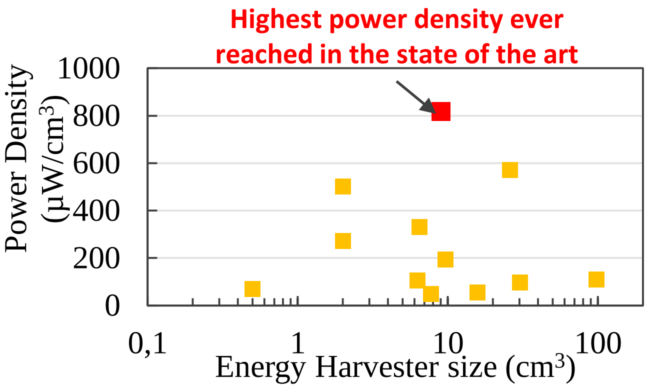
- Concept
  - Electromagnetic shaker
  - Optimized geometry
  - AA-battery size
- Experimental results
  - 9cm³ - inertial mass: 5.74g
  - Run (6.4 km/h): 3.94mW (438µW/cm³)
  - Run (8 km/h): 7,3mW (810µW/cm³)
  - Hand-shaking (6 Hz, 2g): 6,57mW (730µW/cm³)
- Highest power density in the state of the art
- Power Supply of Accelerometer + Bluetooth at 25Hz





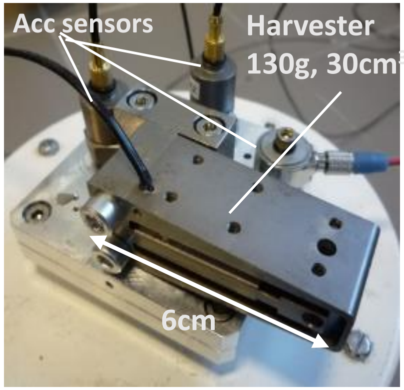




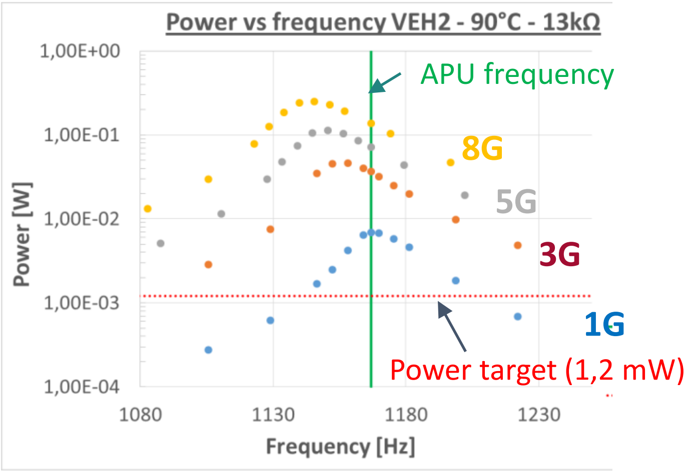


Energy Harvester for Aircraft APUs

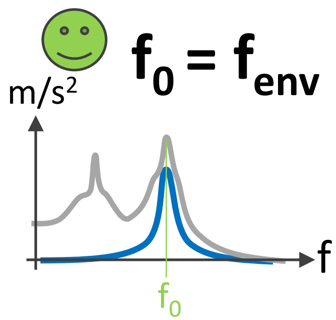
- **Vibration energy harvesting in harsh environments**
  - Piezoelectric resonant structure (cantilever type): designed, simulated (Comsol FEM) and assembled
  - Dedicated power management circuit
  - Application : power supply of 3 acceleration sensors + conditioning stage
  - Constraints :
    - High frequency : 1167Hz
    - High Acceleration :
      - 8G : Pelec > 1,2 mW - Tolerate up to 20G
    - Temperature
      - Operating @ 90°C - 120°C tolerant
  - Results :
    - Vibration tests in climatic chamber validated (8G – 20G @ 90°C and 120°C)
    - Test at the partner's site on a real APU : validated (13G-15G / 70°C)
    - Output power up to 200mW@8G-1167Hz

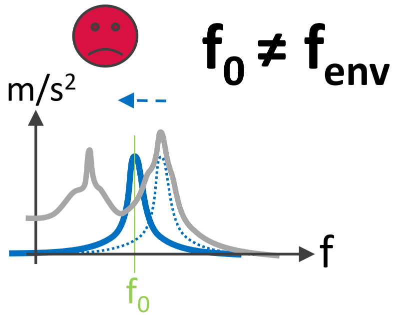


Test Bench CEA

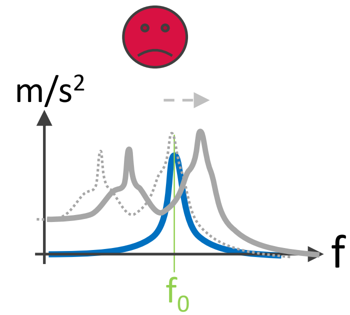


VEH have a limited frequency bandwidth





Drifting of resonant freq (T°, ageing, …)

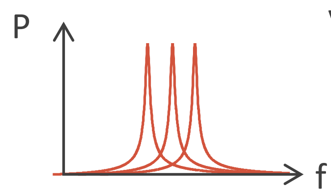


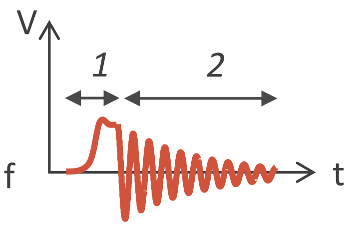
Frequency variation of the environment

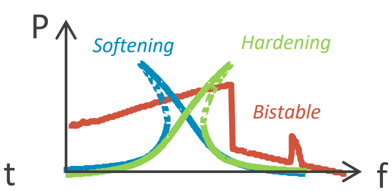
→ Increase VEH frequency bandwidth is the challenge

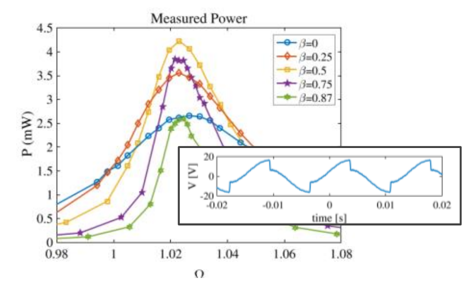
Various approaches to tackle the selectivity of VEHs

- Array of linear generators
- Frequency-up conversion
- Nonlinear oscillators
- **Electrical damping and stiffness tuning**







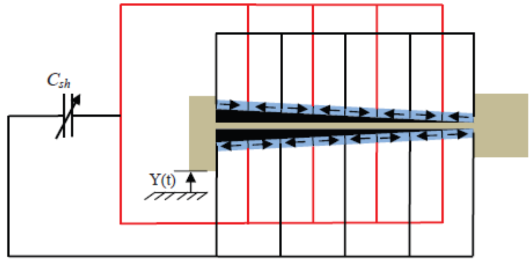


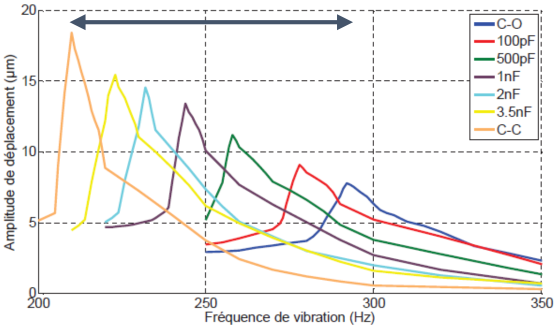
[Lefeuvre *et al.*, 2017]

A solution → Load adaptation on strongly-coupled devices

- Frequency tuning by capacitive adaptation

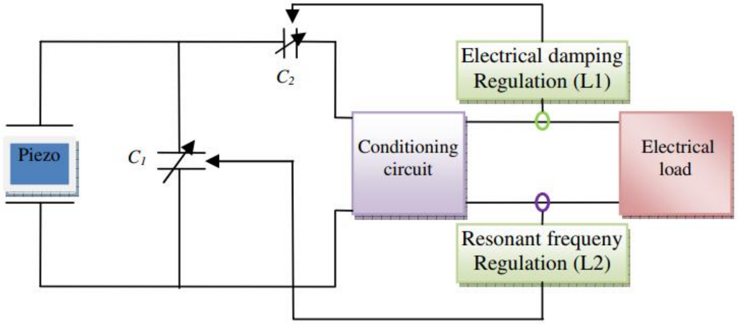
Tuning ratio = 40 % (210Hz – 295Hz)

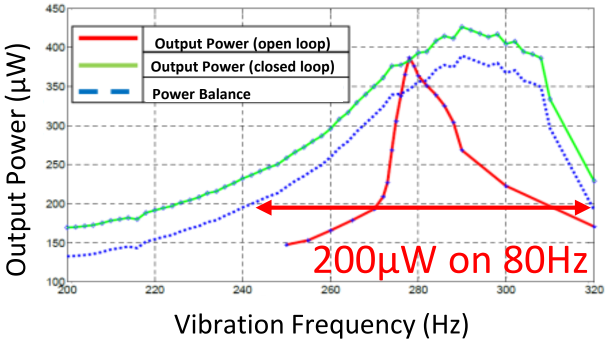




[B. Ahmed-Seddik thesis., 2012]

- Capacitive adaptation: electrical damping and resonant frequency





→ the bandwidth has been multiplied by ≈ 3

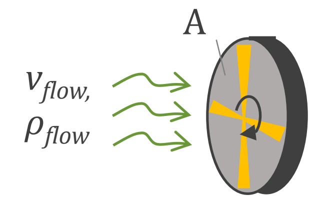
- Circuit consumption : 50µW
- Harvested power : 480µW@0,1g

Proofs of Concept – AirFlow & Water Flow Energy Harvesters

Energy harvesting from flows

- **Power extractable from flows :**

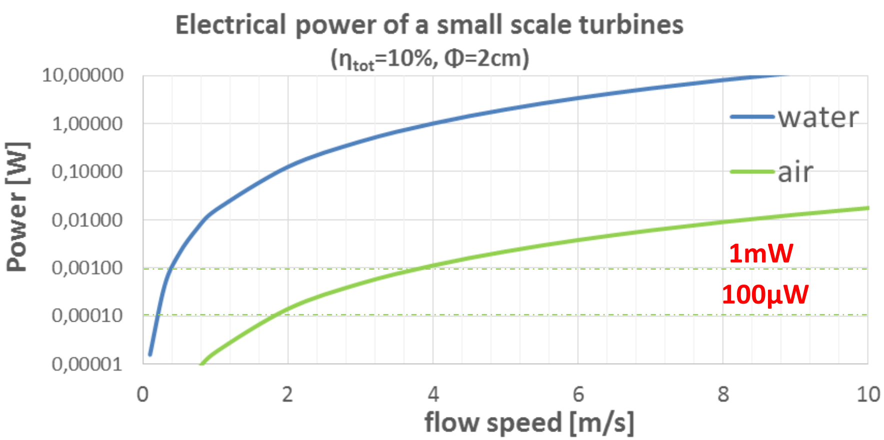
$$P_{elec}[W] = \frac{1}{2} \cdot \eta \cdot \rho_{flow} \cdot A \cdot v_{flow}^{3}$$



  - → Flow driven harvesters are less dependent to environmental conditions
  - (no frequency component)

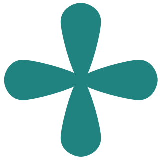
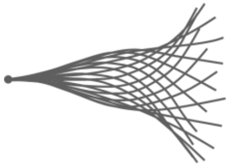
- **Expected powers :**

  - η < 0,59 (Betz's law)
  - 0,3 < η < 0,4 for typical windmills
  - **η < 0,2 for small scale devices**



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

→ Low fluid speeds : our target

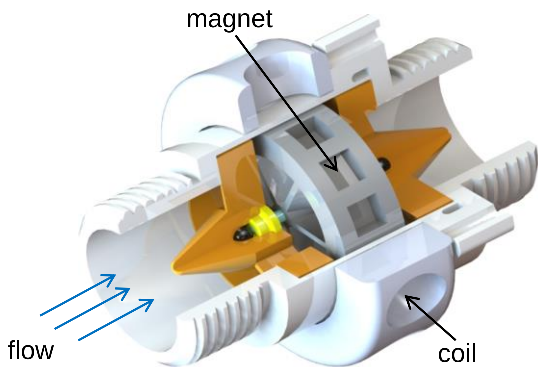



- **Various types of conversion : rotation vs fluttering**

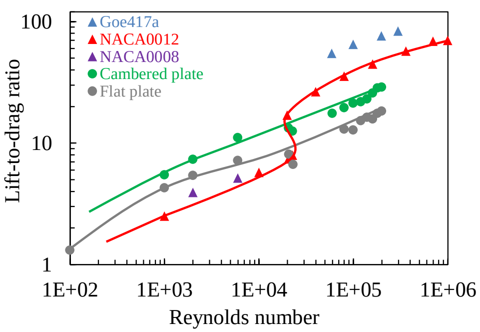
Water Flow Energy Harvesters

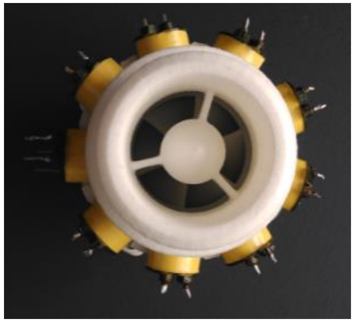
Horizontal axis water flow turbine

- Concept
  - Coreless Permanent magnet generator => cogging issues
  - Distributed magnets at the periphery of the turbine with alternate polarities

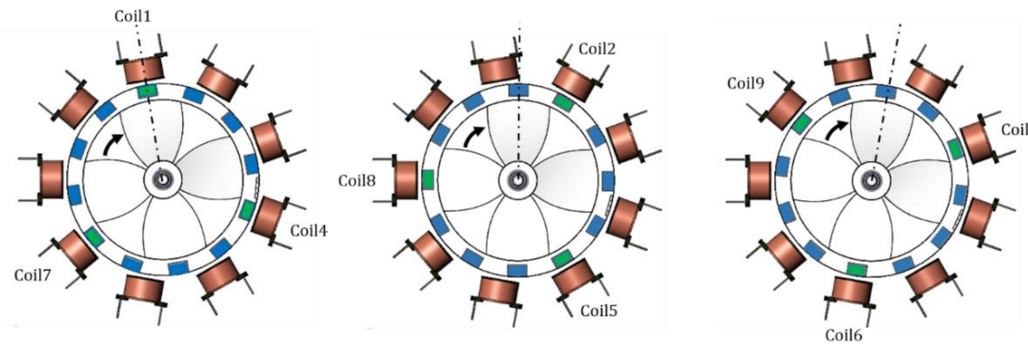


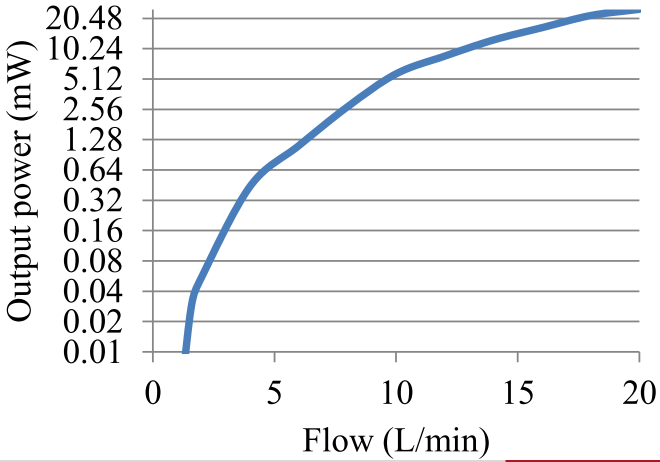
- Experimental results
  - 7,5mW@10L/min – 32mW@20L/min
  - Δp=0.05bars@30L/min (all coils short-circuited)
  - KEH=3.94 consistent with minor loss coefficients of turbine flowmeters





- Lowest pressure loss in the state of the art

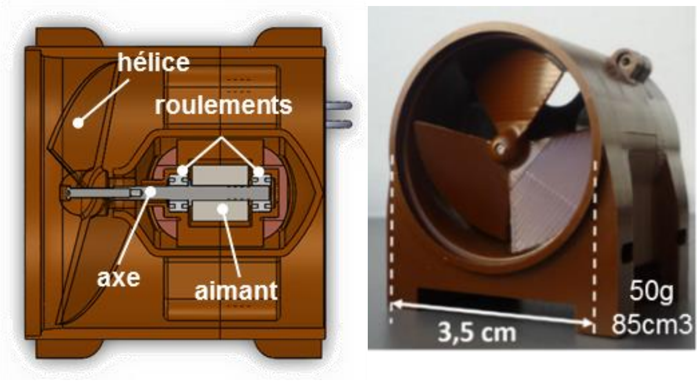




Energy Harvester for Aeronautic Applications

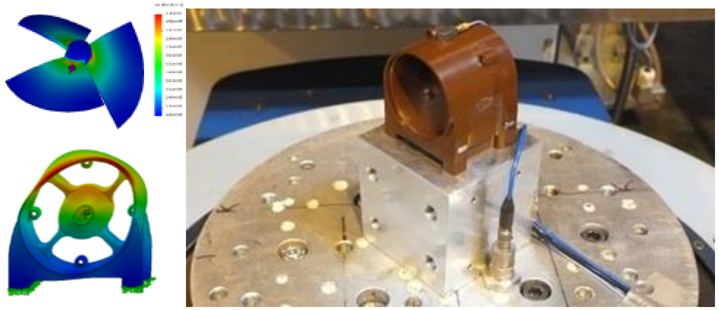
▶ Air flow energy harvesting in harsh environment

- Microturbine dedicated to :
  - Very low air flows [3-10m/s]
  - Tolerant to aeronautic environments [250°C – acc of 20G]



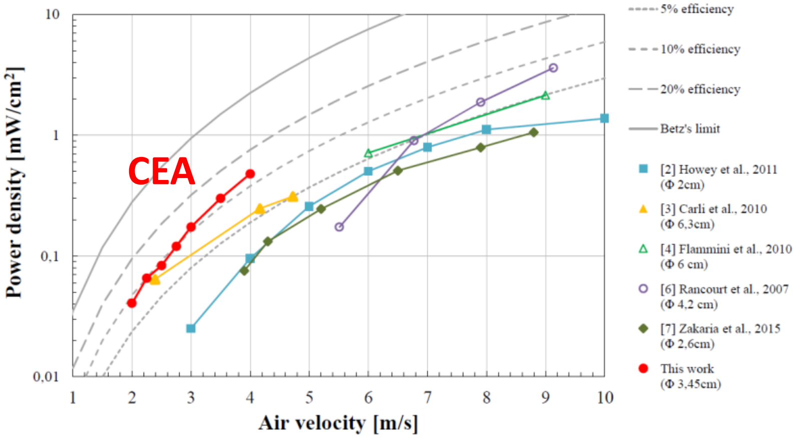
- High temperature materials
  - Bearings, copper wire and SmCo magnet
  - Carter and propeller machined in polyimide (Vespel)

- FEM Simulations of vibrational behavior
- and selection of a robust design (20G)



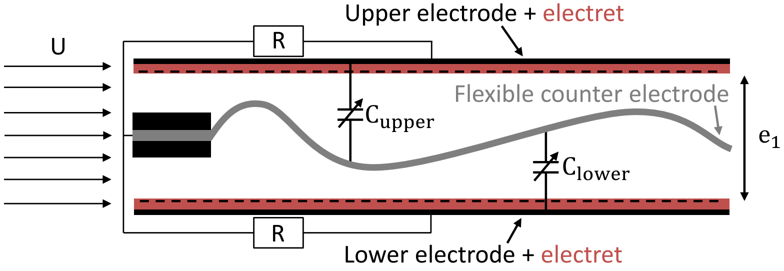
Vibration tests

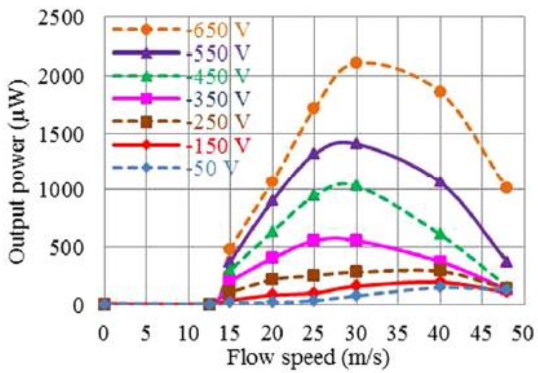
- Results :
  - Resistance testing (10^7cycles 20G on the res. modes)
  - Temperature ageing (4h at 250°C / 240h at 180°C)
  - Output powers @ 25°C :
    - Wind tunnel tests :1mW$_{rms}$ @ 2,5m/s
    - Efficiency: 10% (higher than the state of the art)

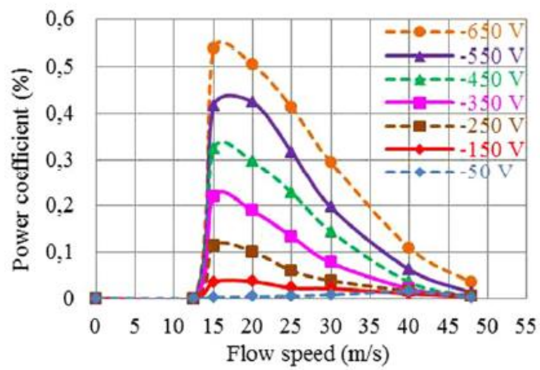


Energy harvesting from flows

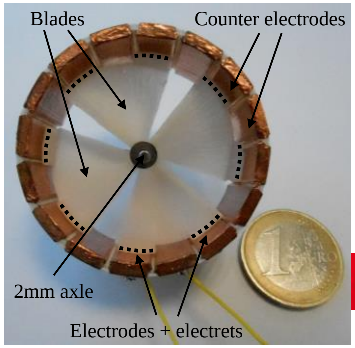
- **Air flow energy harvesting with electrostatic converters**
  - Electret-based aeroelastic flutter energy harvester
    - Flexible membrane in oscillation due to fluttering and comes into contact with two Teflon-coated fixed electrodes
    - 481 µW @ 15 m/s and 2.1mW @ 30m/s
    - Drawbacks : high cut-in speeds (10 - 15 m/s)





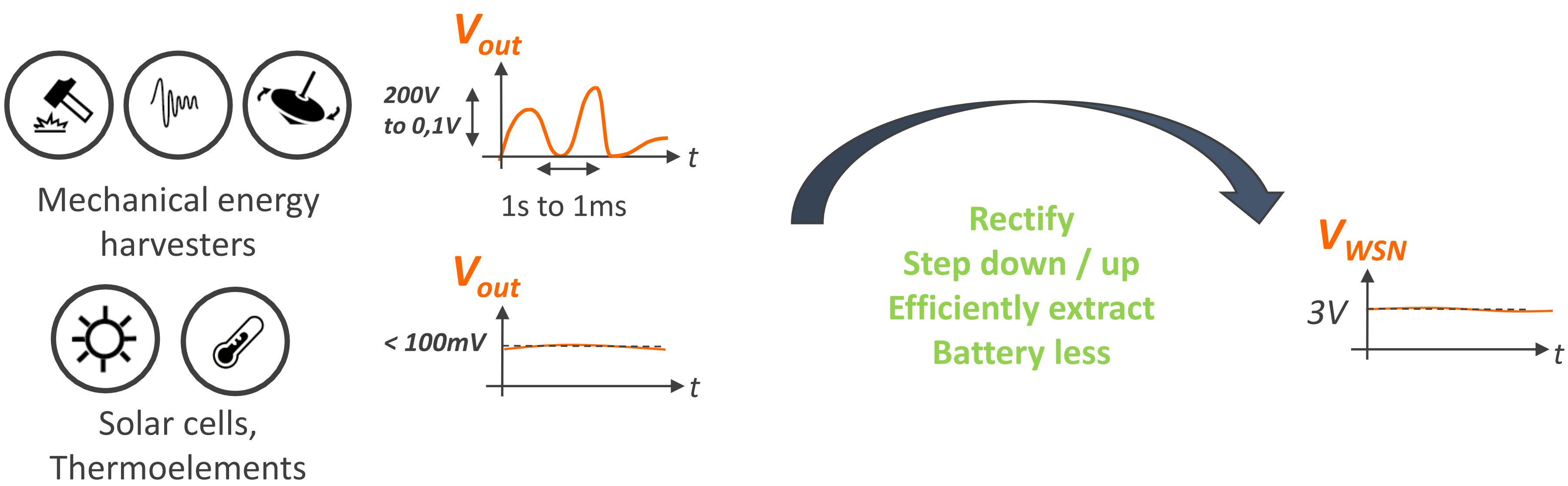


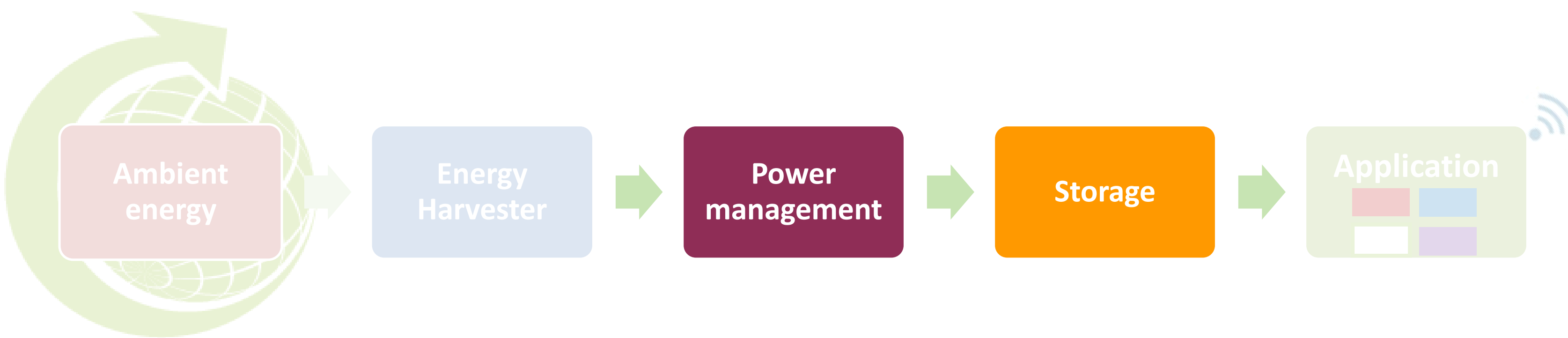
    - → Enables flat form and low volume devices (2.7 cm³ here)
  - Electret-based electrostatic wind turbine
    - Ø= 40 mm - 12.6 cm³
    - Low powers : 1.8mW at 10 m/s, C_{pmax}= 5,8%
    - Lowest cut-in speed of the SOA : 1.5 m/s (90 µW)



Proofs of Concept – Power Management Circuits

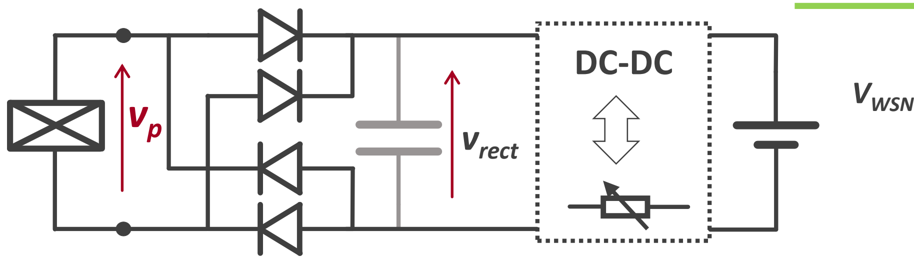
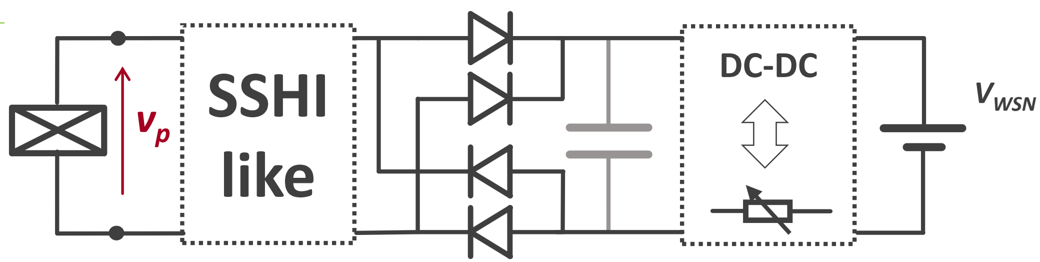
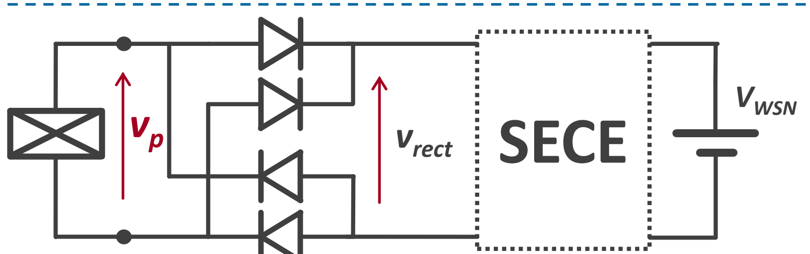
Power management circuit : what for ?





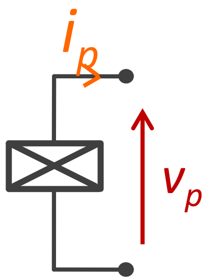
Power management circuits

- For lowly-coupled piezoelectric energy harvesters

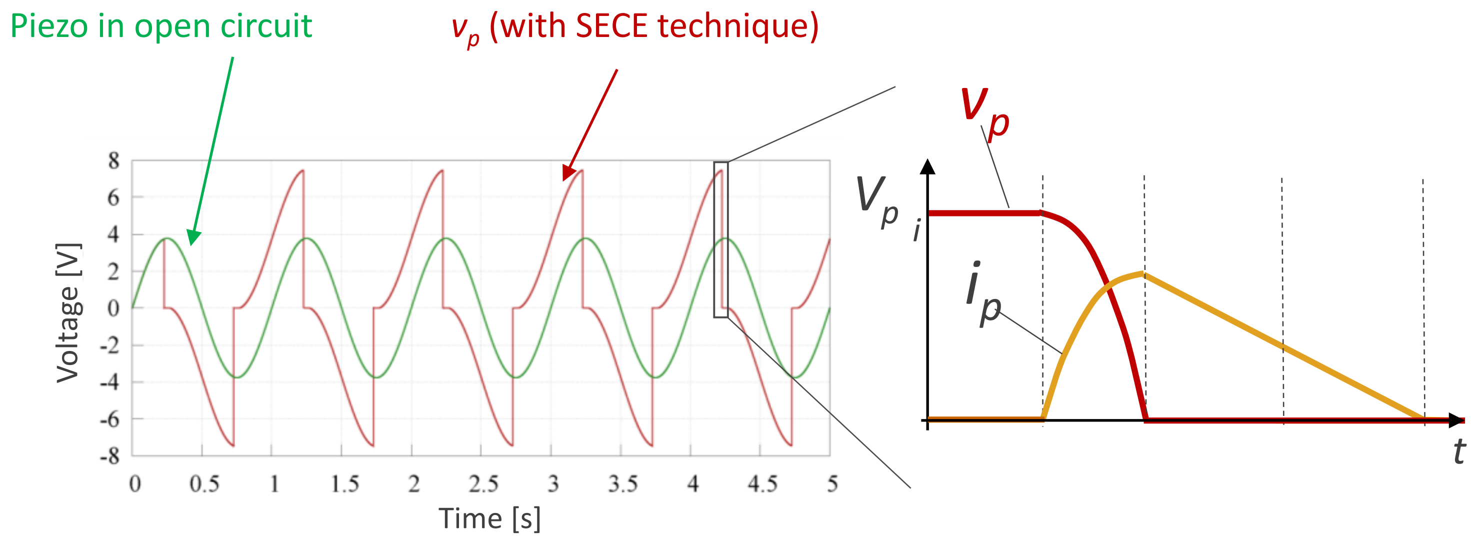
		Harvestable power	Implementation
Standard technique			 MPP required, + depends on the reactivity of the DC-DC's switching frequency
Non linear techniques			 two inductive elements + idem standard technique
	 [Lefeuvre *et al.*, 2005]		 Independecy from the load, only one inductive element

- → SECE = Very good compromise btw performance and complexity / nb of components

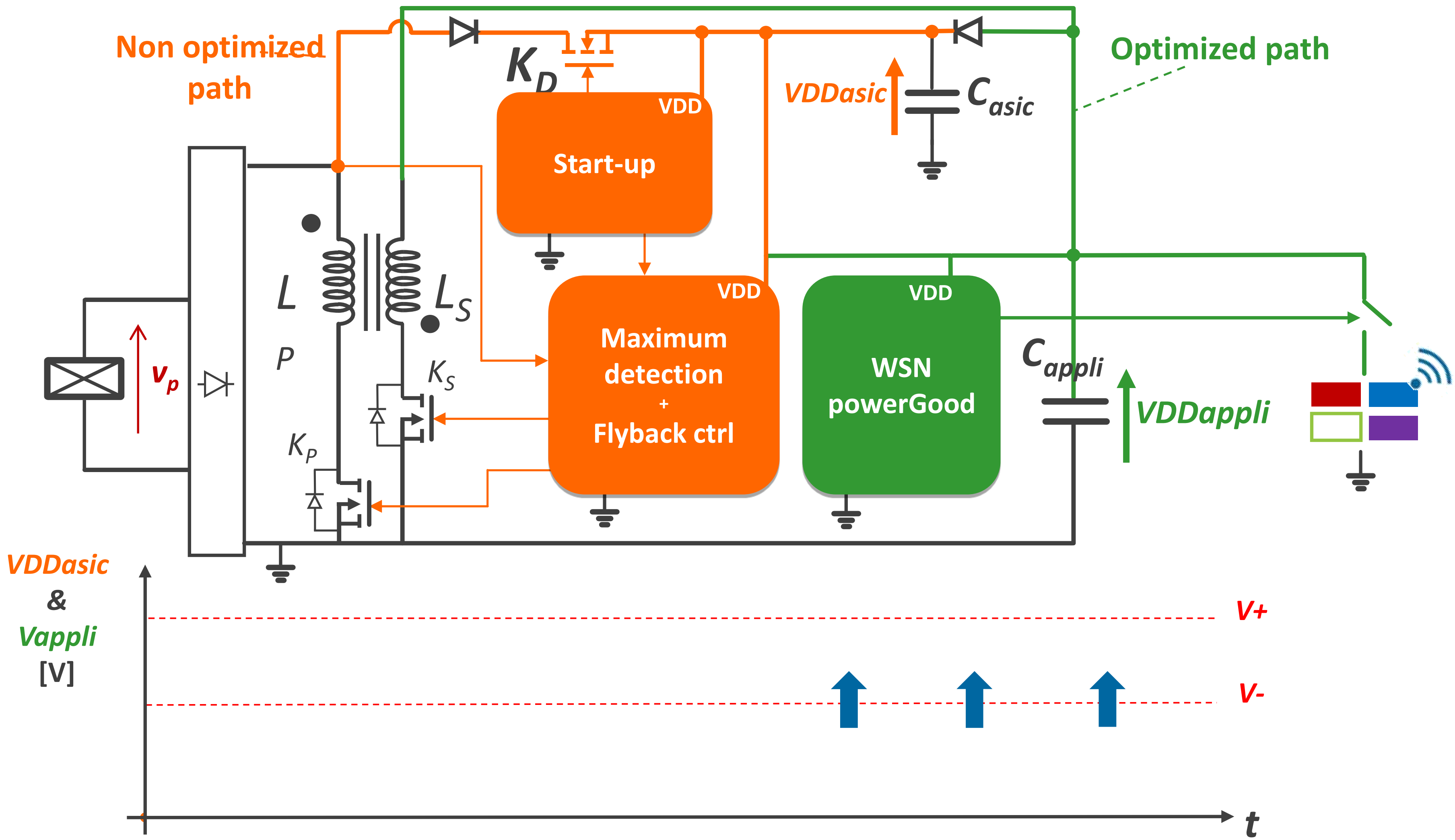
SECE technique : operation mode



Piezoelectric harvester



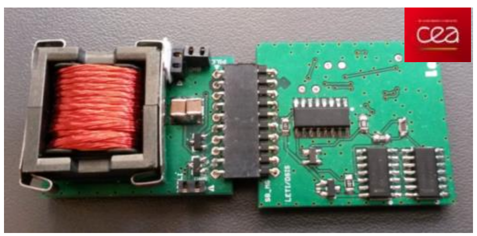
- Implementation of the battery-less SECE technique



- Implementation for electrostatic and piezoelectric harvesters
  - Autonomy & Self-starting on capacitors, very low power (<1µA)
  - Two approaches :

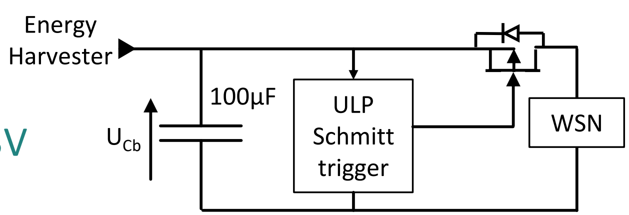
Discrete components :

1µA@3V

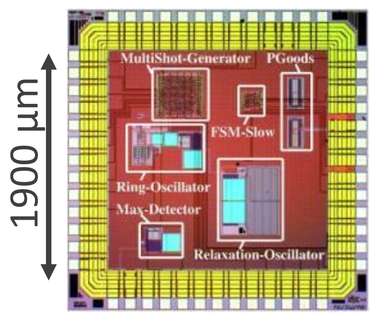


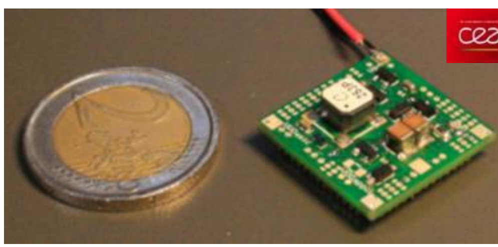
Ultra-low power Schmitt trigger

<50nA@3V



Hybrid approach :
IC + Discrete power circuit



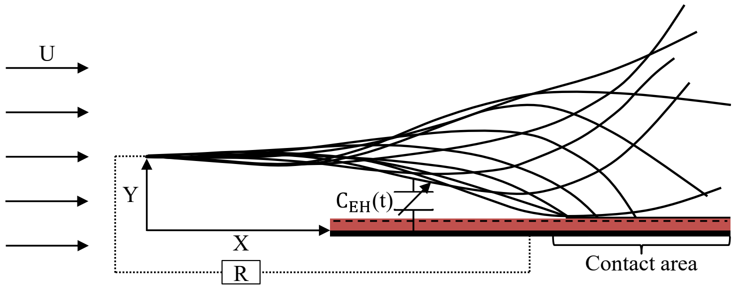


- AMS 0.35 µm technology
- Power consumption : 1 µW @ 5 Hz / 5 µW @ 100 Hz
- Multishot technique MS-SECE

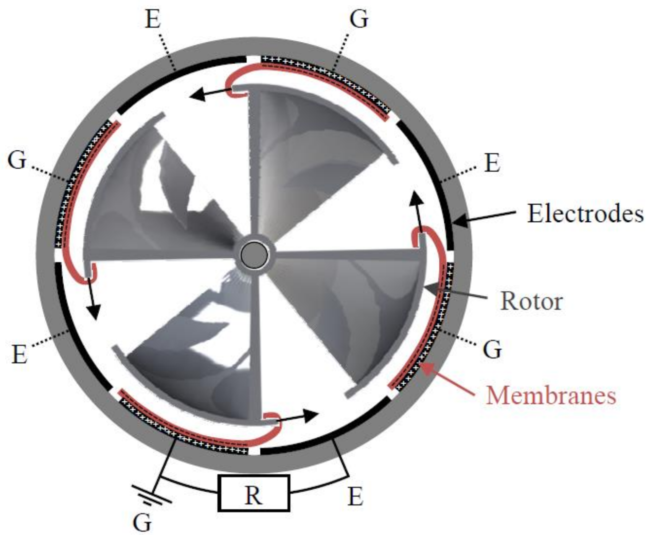
→ Down to 200nW harvested

Power management circuits

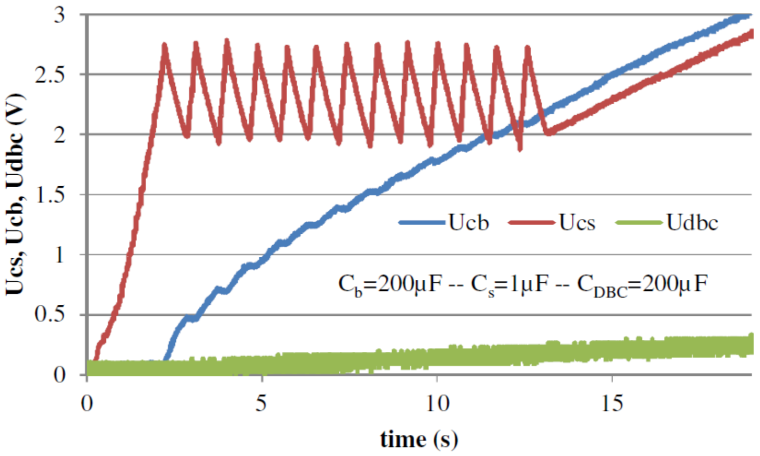
- Fluttering

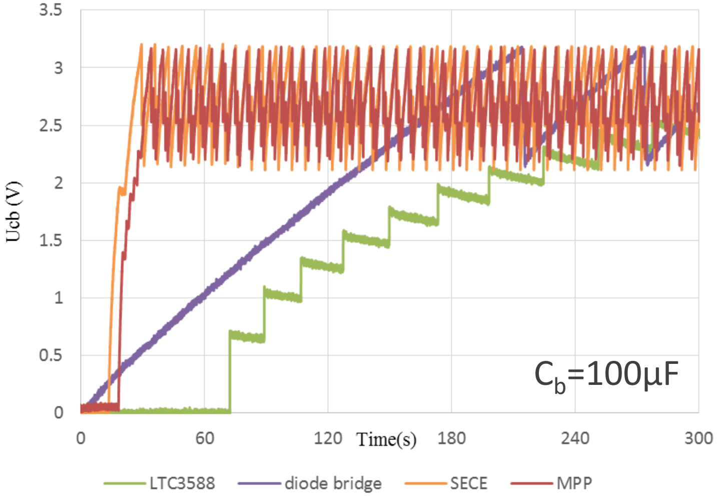


- Triboelectric turbines



▶×150 vs diode bridge





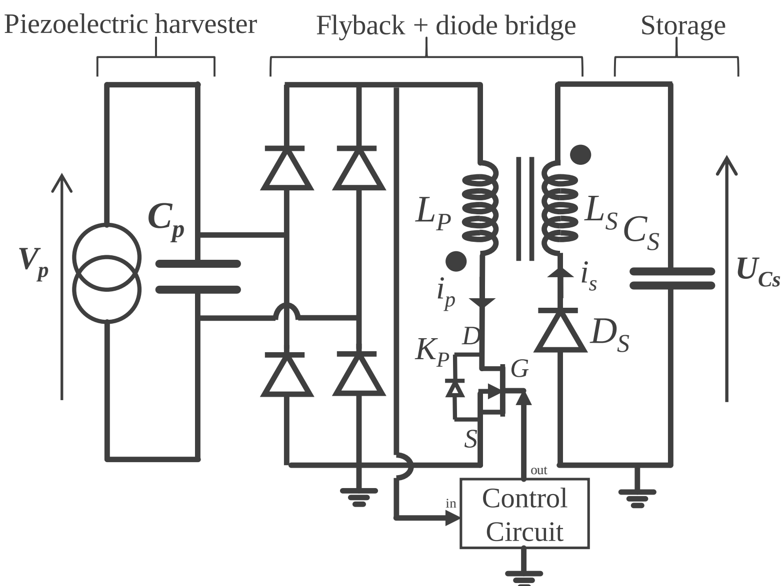
▶SECE≈MPP>DBR>LTC3588

Compatibility with EH in parallel

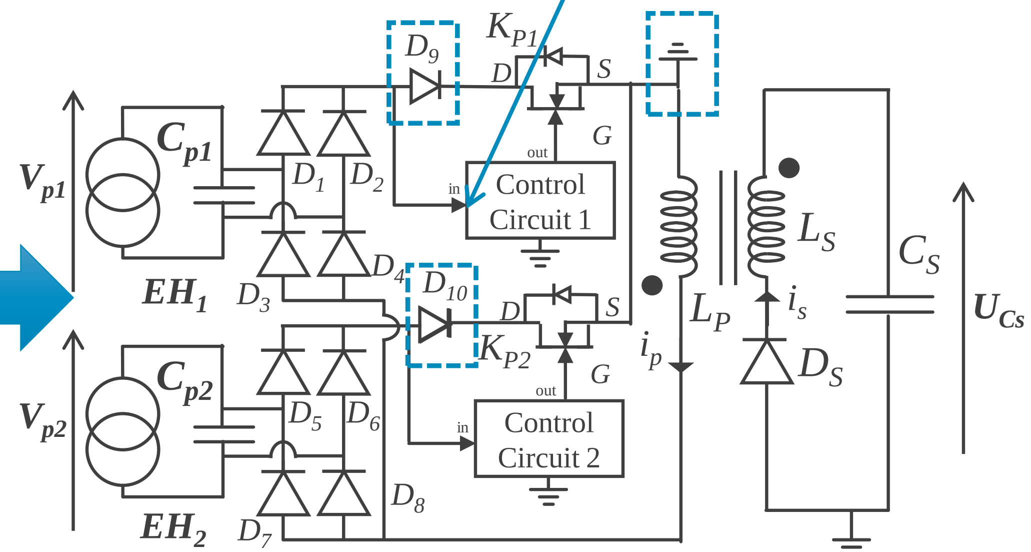
From SECE for single EH to SECE for multiple EH

- Constraints
  - Detecting the maximum output voltage of each Energy Harvester
  - Discharging only the energy harvester that has reached its maximum output voltage
  - Mutualizing the components (coupled inductor)

Max voltage detection with a capacitor



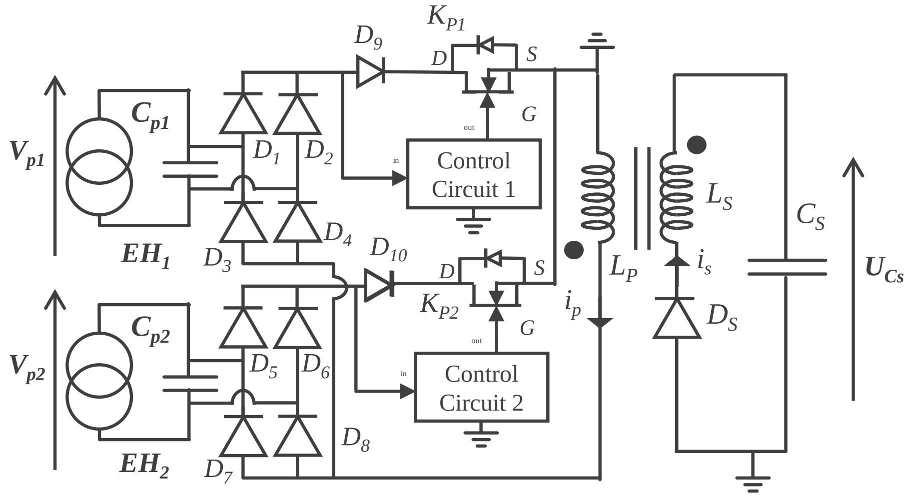
SECE for single EH

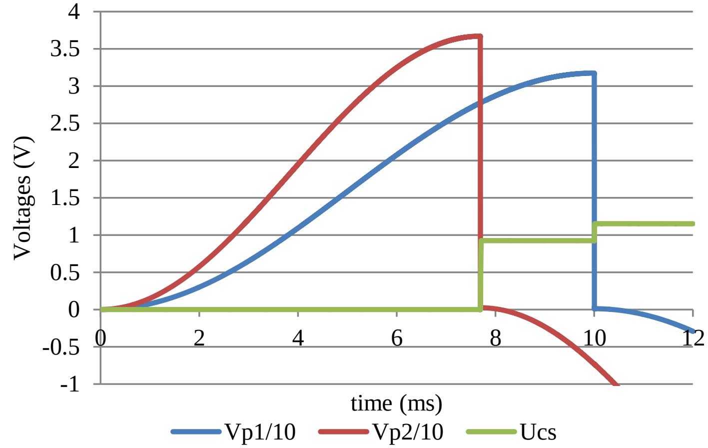


SECE for multiple EH

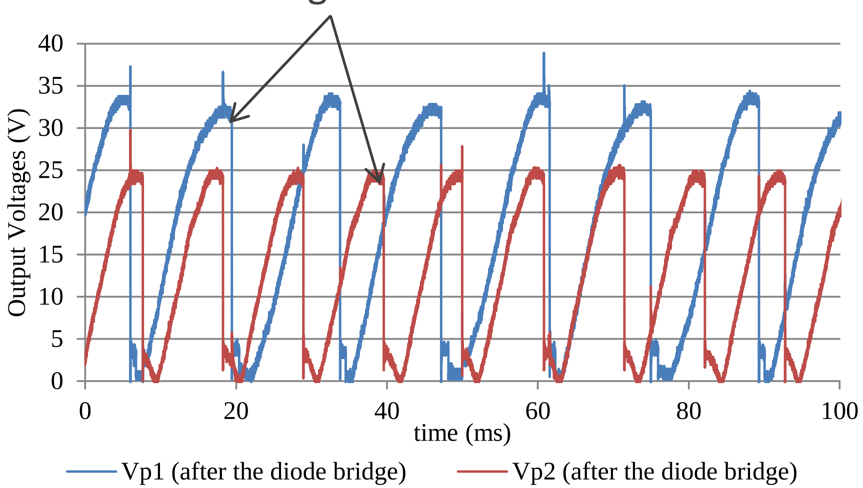
Compatibility with EH in parallel

- **Spice Simulations with 2 Energy Harvesters**





  - Discharging EH1 does not discharge EH2

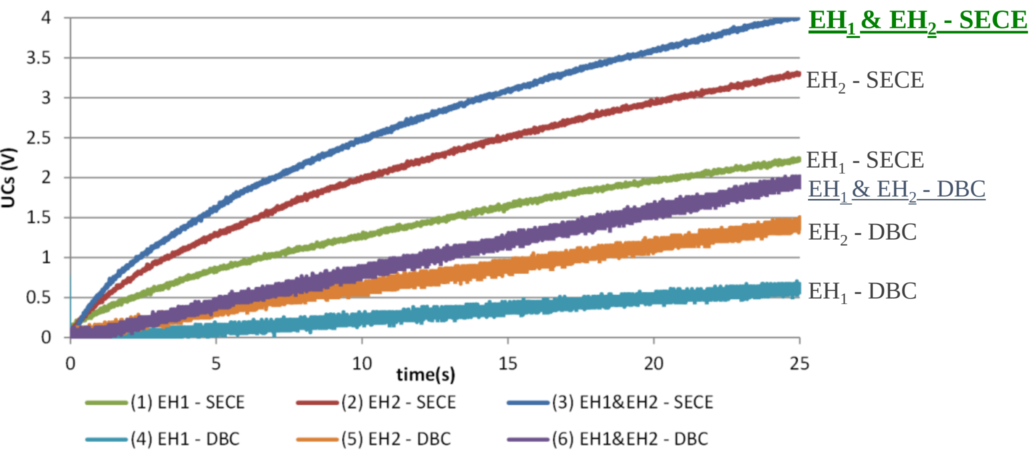


- **Experimental validation**
  - EH1: C_{p1}=5.8nF, $V_{p1[SECE]}$=34V, f_{p1}=36Hz
  - EH2: C_{p2}=17.6nF, $V_{p2[SECE]}$=24V, f_{p2}=47Hz
  - Placed on two different shakers

Compatibility with EH in parallel

Output powers and efficiencies

- Output energy on a 940µF buffer capacitor



	Configuration	E_{Cs25} (Stored Energy in C_s=940µF after 25s)
EH_1 alone	(4) DBC	0.16mJ
	(1) SECE	2.27mJ
EH_2 alone	(5) DBC	0.92mJ
	(2) SECE	4.99mJ
EH_1&EH_2	(6) DBC	1.71mJ
	(3) SECE	7.52mJ

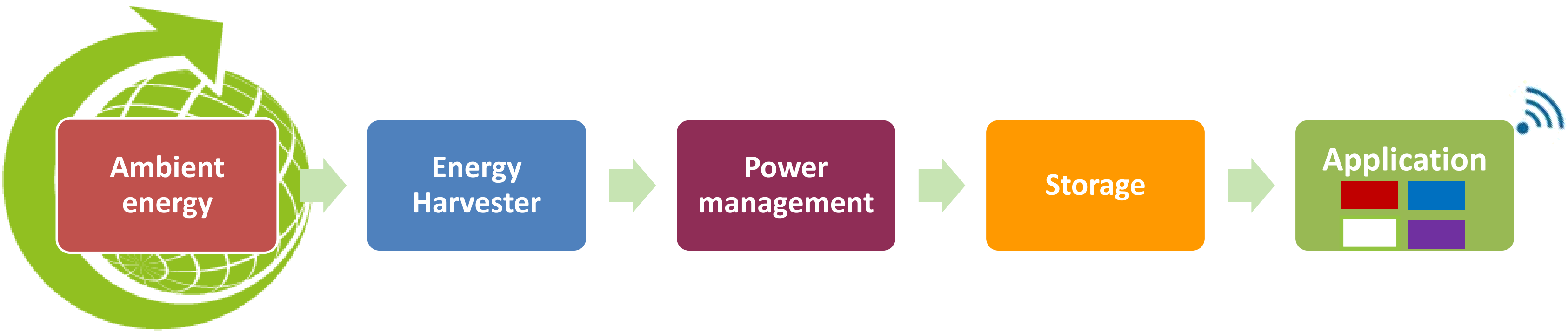
- E_{SECE}(EH1)+E_{SECE}(EH2)≈E_{SECE}(EH1+EH2)
- E_{SECE}(EH1+EH2)>4xE_{DBC}(EH1+EH2) => High benefit of SECE for Energy Harvesters in parallel
- Max conversion efficiency: 83%
- Control circuit power consumption: 1.15µA@3V per energy harvester
- Battery-free operation mode

Conclusions

Conclusions

- **EH-powered sensor nodes ⇒ Already a reality**
  - Possible to supply wireless sensor nodes down to 200nW harvested
  - Many sources available: light, thermal gradients, flows, shocks, vibrations…. and compatible with the power supply of wireless devices and especially sensors
  - Global system vision required : EH + Power Management + Low-power sensor node with optimizations and compromises at each stage

- **EH@CEA ⇒ Complete energy harvesting chains**
  - Materials: PV cells, thermoelectric, piezoelectric materials, magnets…
  - Energy harvesters (vibrations, flows, human movements,…)
  - Power management circuits with discrete components and ASICs
  - Low-power Wireless Sensor Nodes



JNRSE2020 - SAVE THE DATE!

JNRSE 2020

CEA Grenoble, 27-28 May 2020

10th National Days on Energy Harvesting and Storage

Important dates

Abstract submission deadline : **17 April 2020**

Conference days : **27-28 may 2020**

https://jnrse-2020.sciencesconf.org