# Autonomous Powering of Wireless Sensors for Gas Turbine Applications

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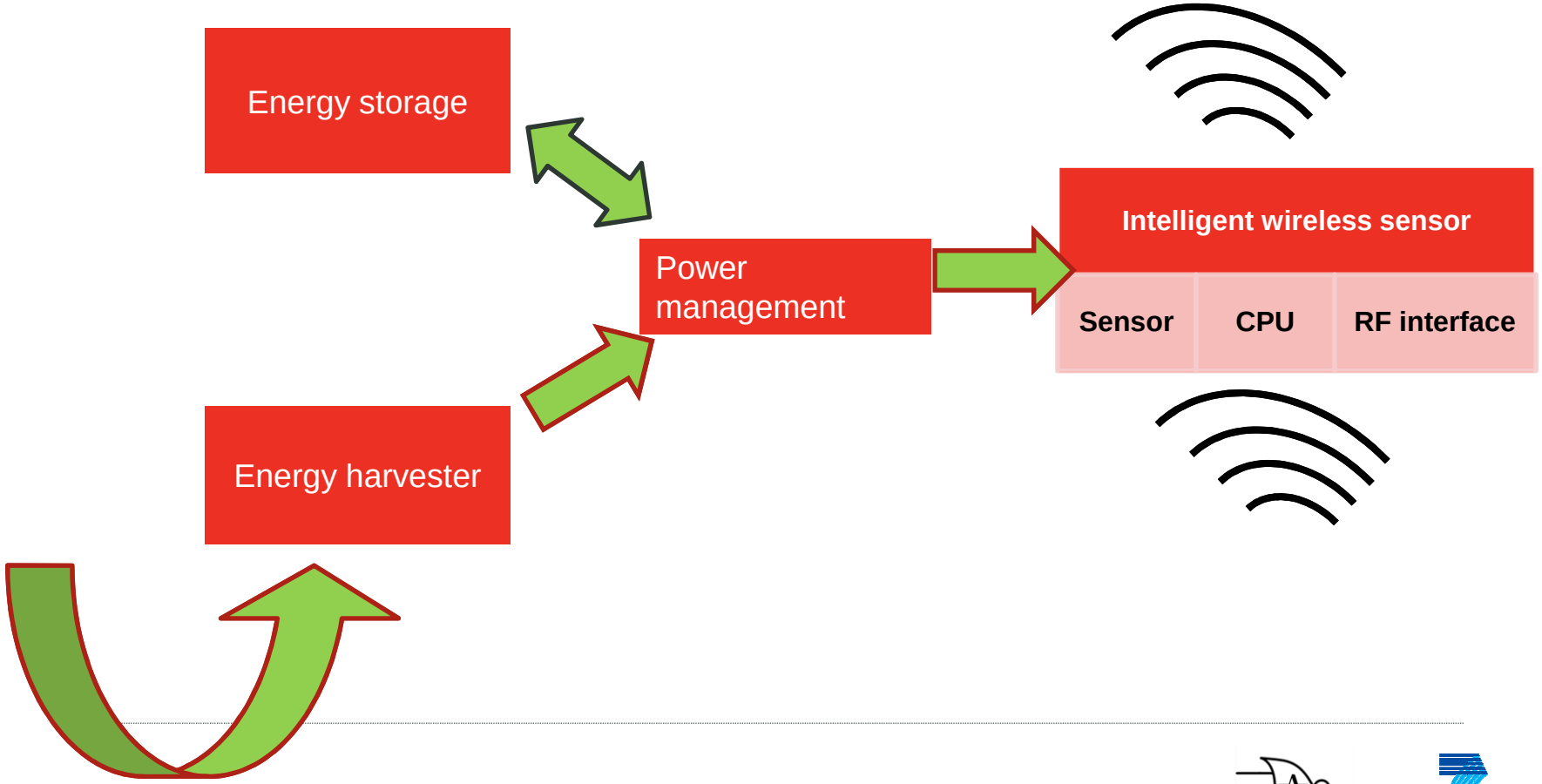
SEVENTH FRAMEWORK PROGRAMME

# Outline

- Wireless sensors
- Energy harvesting
- Piezoelectric Harvester
  - Materials and Design
  - Measurements and Results
- Thermoelectric harvester
  - Materials and Design
  - Measurements and Results
- Energy storage
  - Supercapacitors
  - Materials and Results
- Conclusion

# Introduction - What are Intelligent wireless sensor systems?



# Introduction - Applications

- Environmental Monitoring
- Habitat Monitoring (light, temperature, humidity)
  - Integrated Biology
- Structural Monitoring
- Interactive and Control
  - RFID, Real Time Locator, TAGS
  - Building, Automation
  - Transport Tracking, Cars sensors
- Surveillance
  - Pursuer-Evader
  - Intrusion Detection
  - Interactive museum exhibits
- Medical remote sensing
  - Emergency medical response
  - Monitoring, pacemaker, defibrillators
- Military applications and Aerospace

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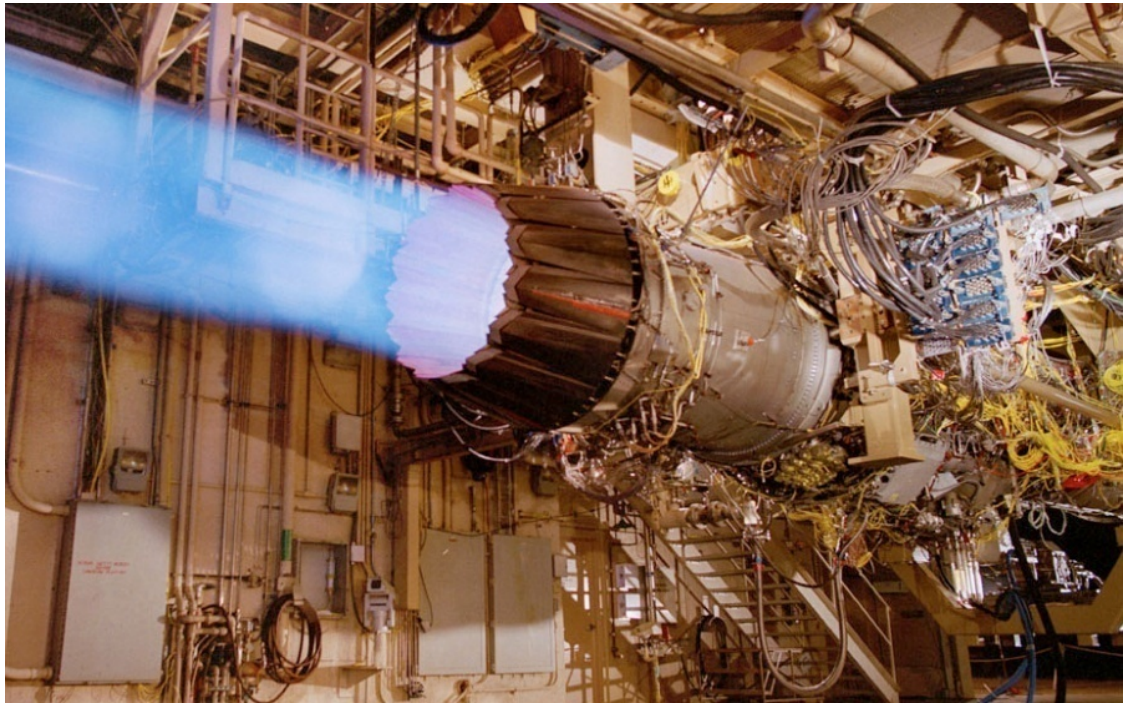
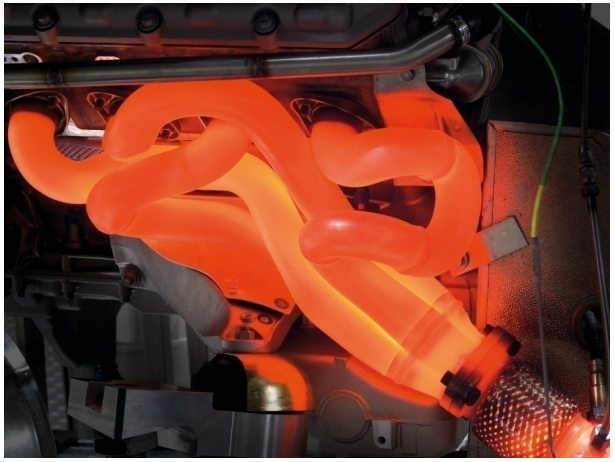
# Introduction - Sensors

- Test gas turbines
  - 1500 sensors
  - 19 km cable

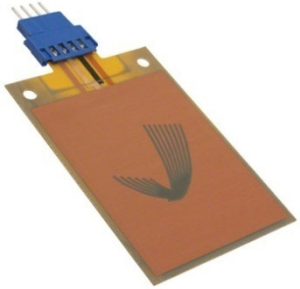


# Energy Harvesting

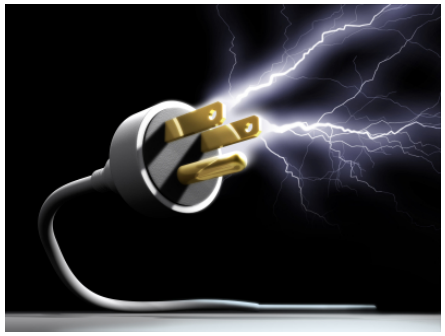
Vibrations



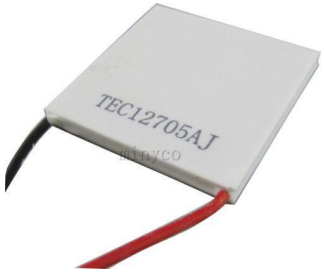
Heat



Piezoelectric energy harvester



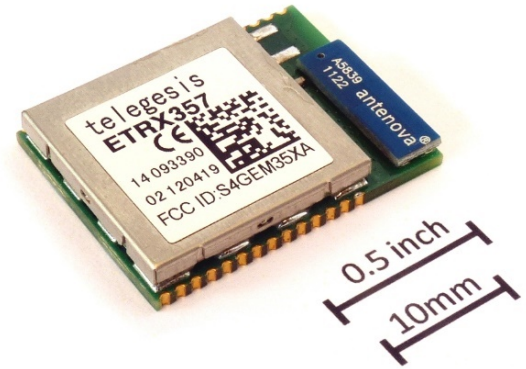
Power!

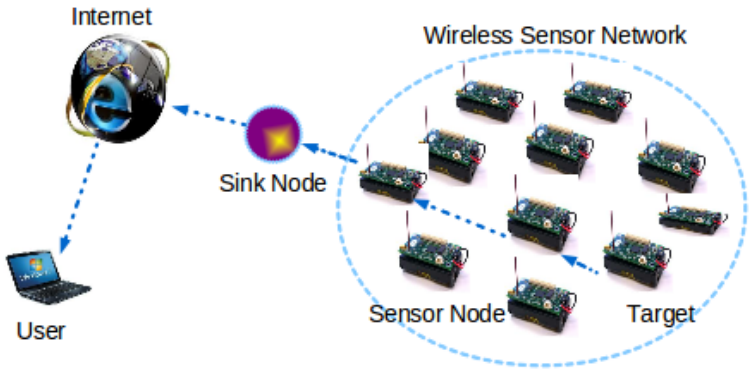



Thermoelectric energy harvester

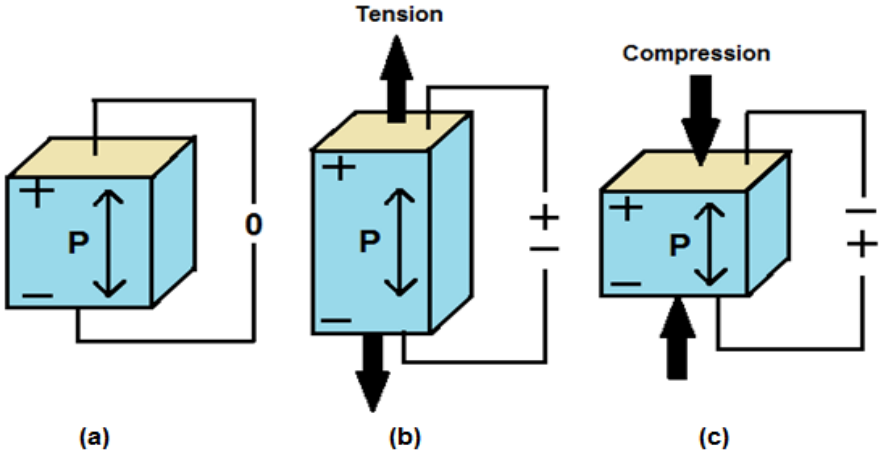
# Introduction – Wireless sensors

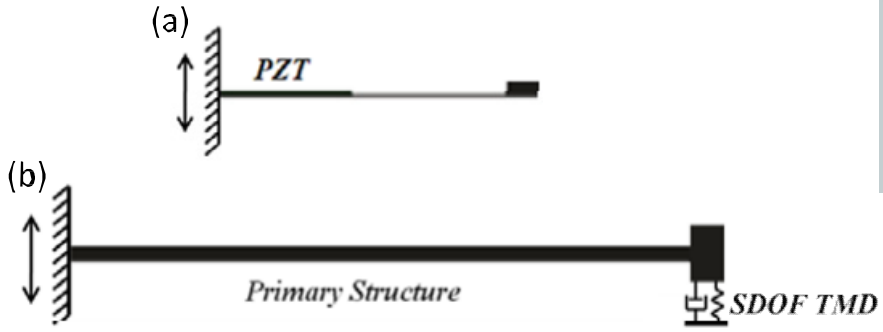
- Wireless sensor (network)
  - ZigBee 802.15.4
- Power
  - WIFI startup 60 – 240 mW
  - Transmitting is 4 - 8 mW
- Several sensors possible

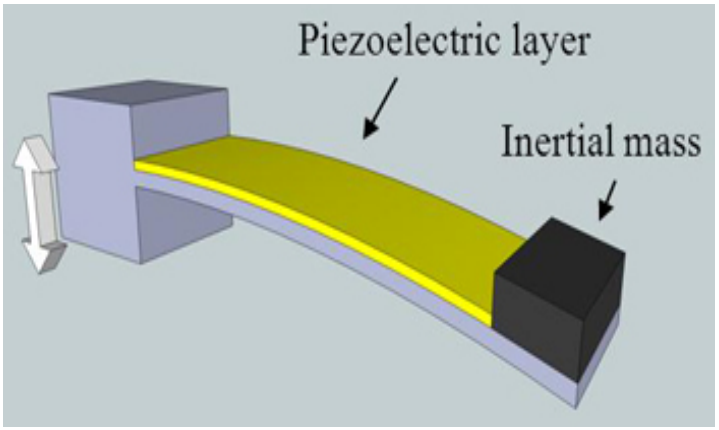


# Piezoelectric energy harvesting

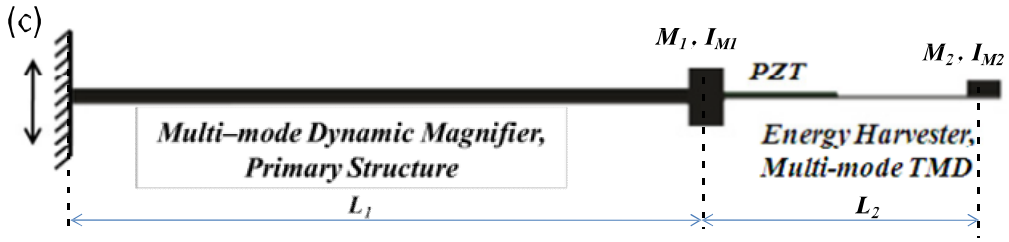


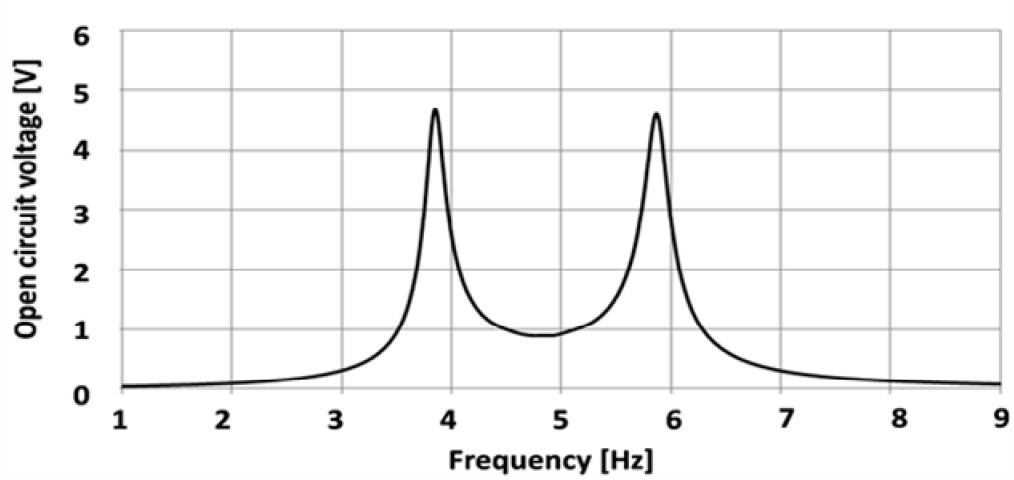



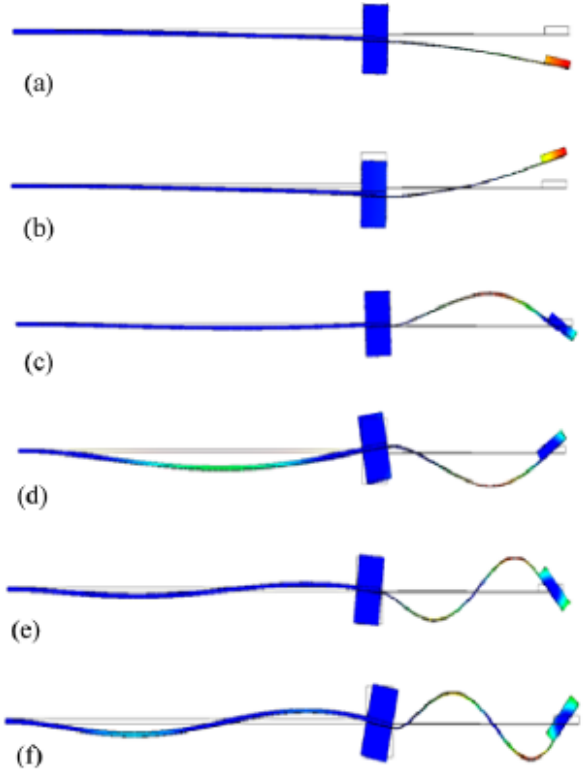

(a) A typical energy harvester
(a) Classical TMD for a beam

# Piezoelectric energy harvesting - 2DOF

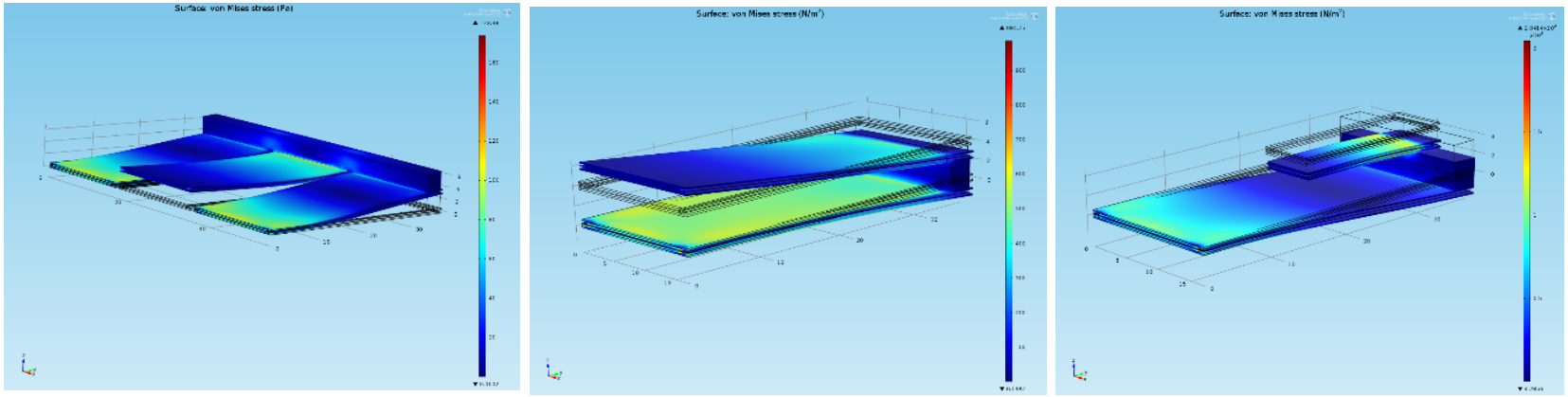


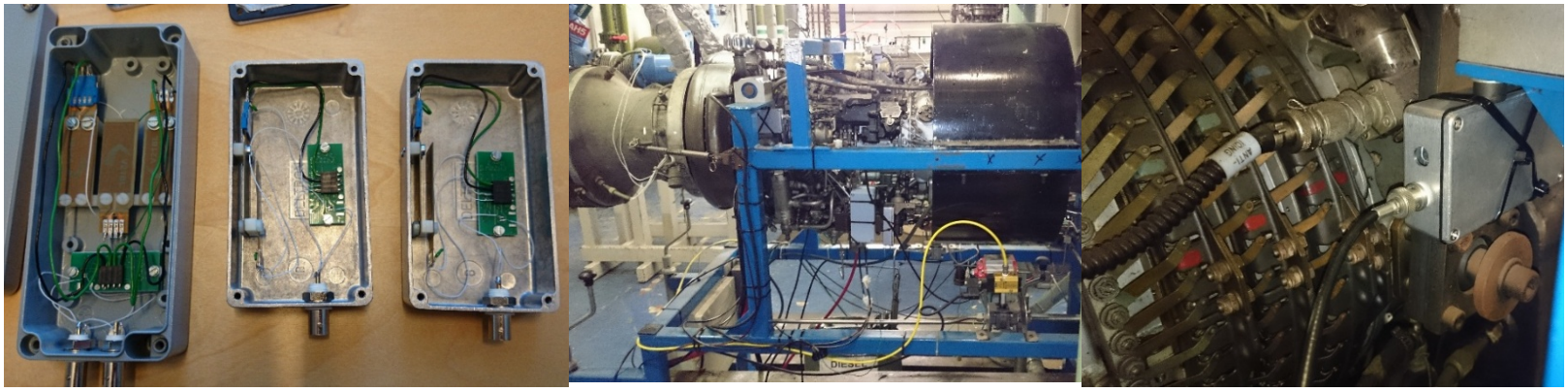

(c) Multi-mode double beam harvester or TMD.



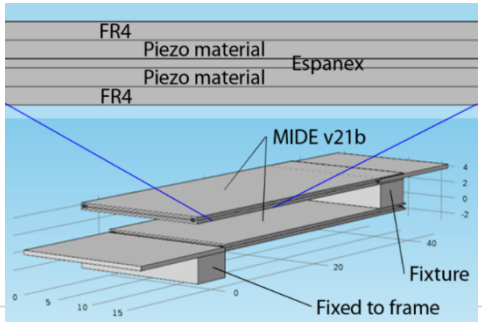
# Piezoelectric energy harvesting – 2DOF Coupled harvesters

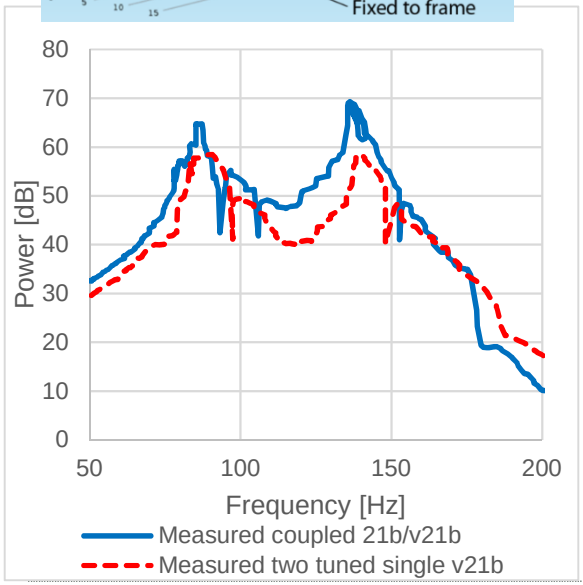


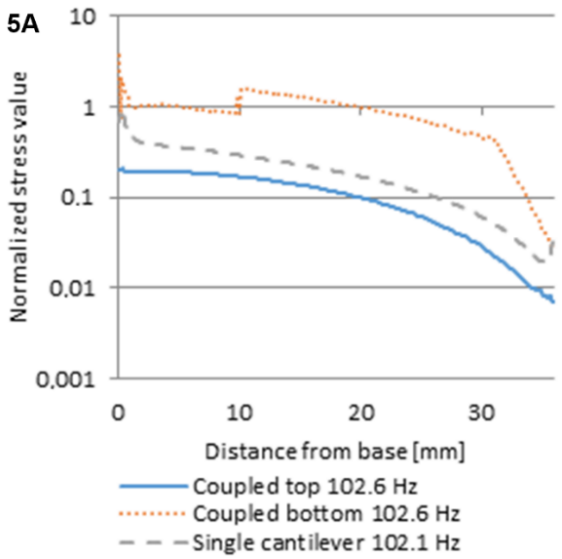


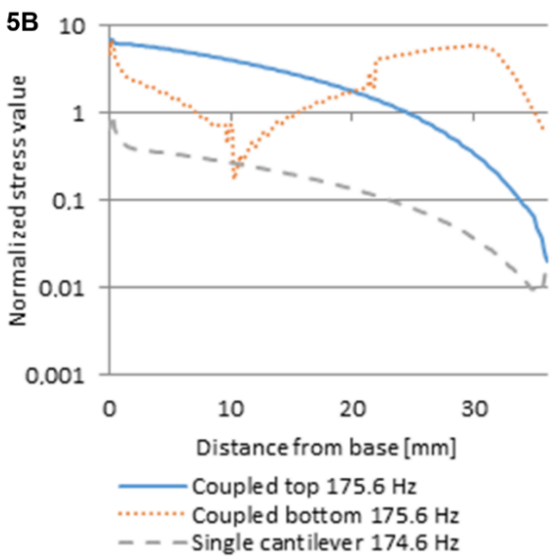
Harvester tested up to 100 °C, without problems

# Piezoelectric energy harvesting – Broader bandwidth by coupling effect



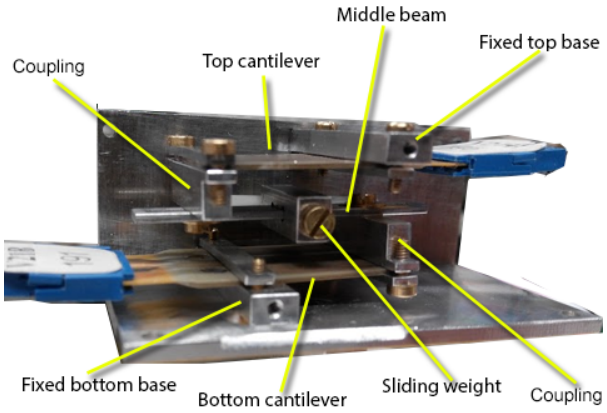



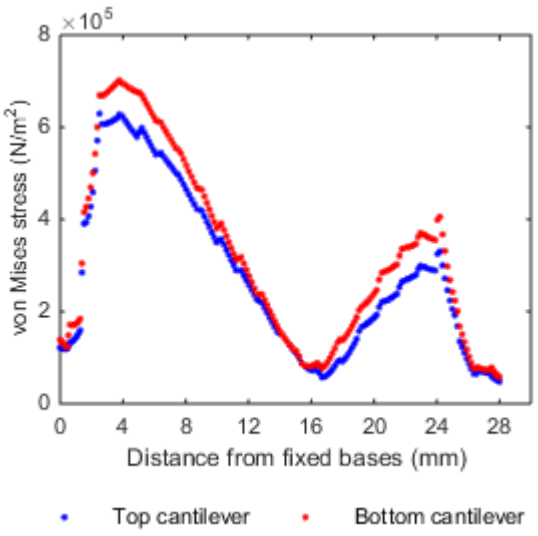



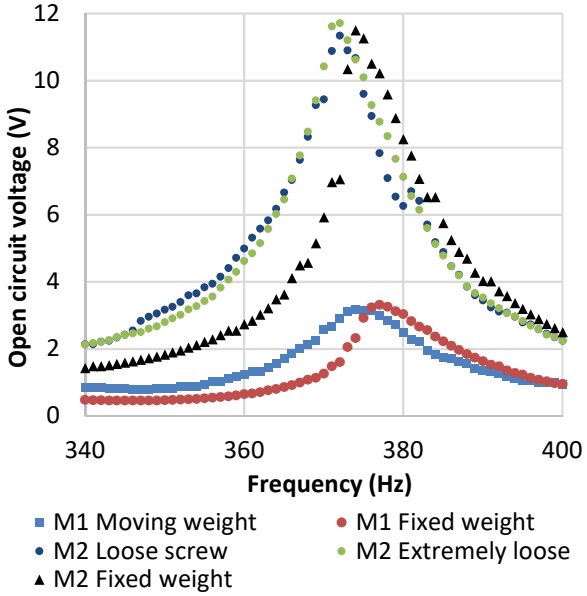



# Self-tuning - vibration harvester

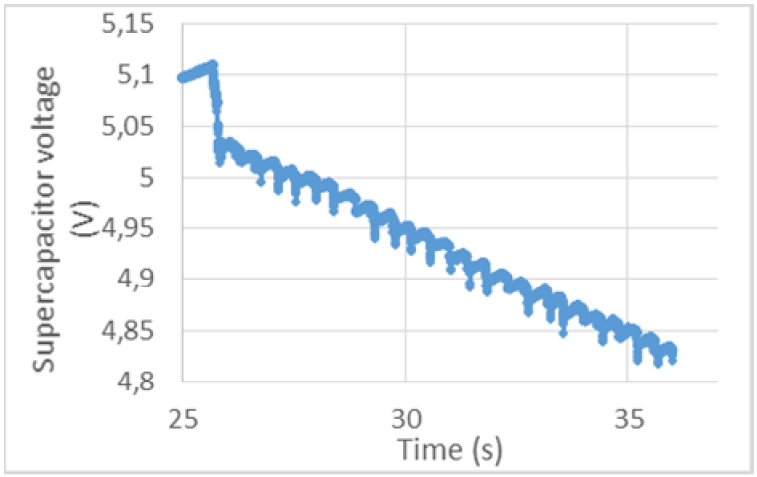
- Self-tuning harvester
  - Broader bandwidth
  - High power output, depending on resonance of the coupling beam

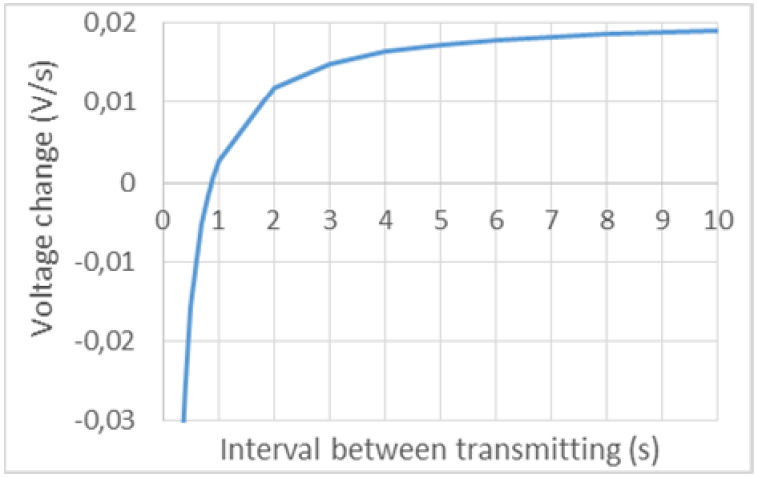


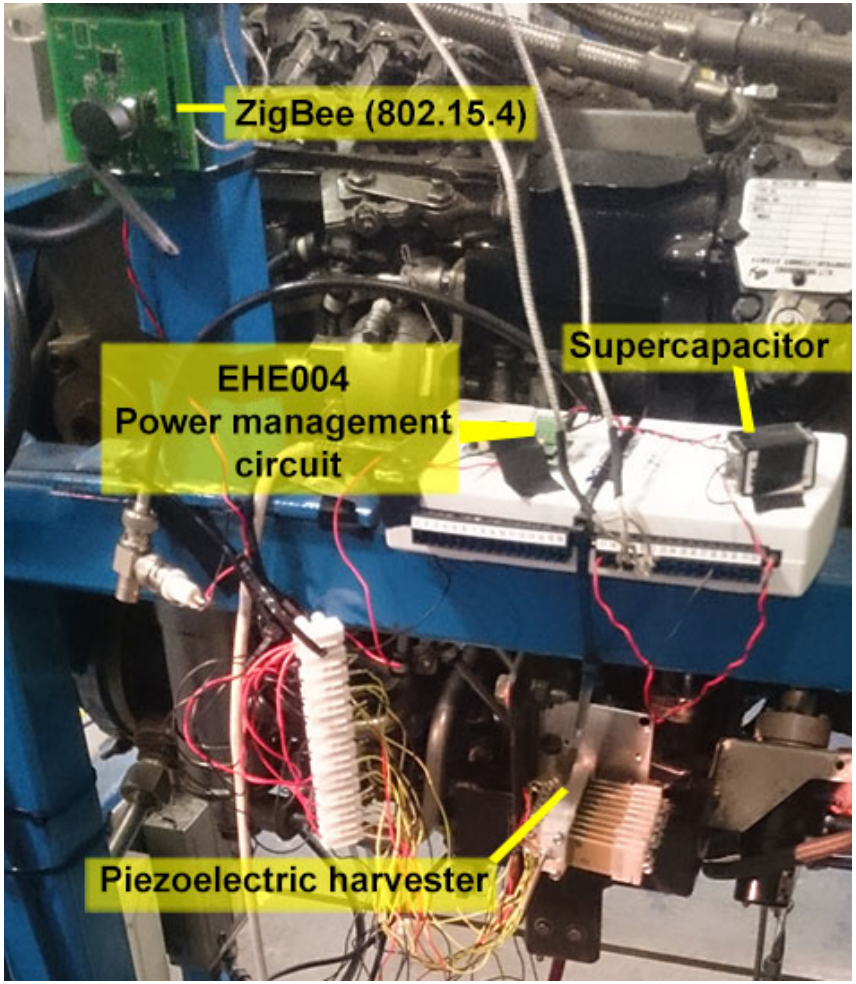



# Results on gas turbine - powering IWS

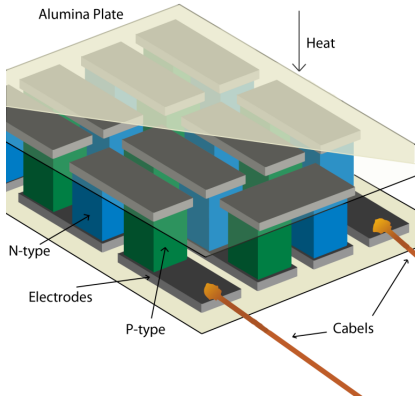


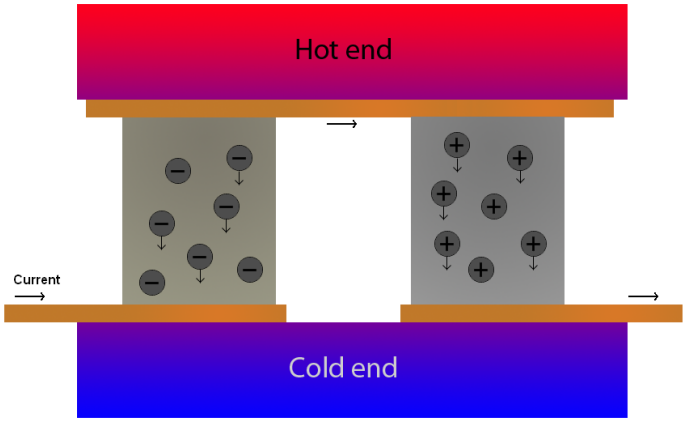



# Thermoelectric Energy Harvester

- Thermoelectric materials
  - Temperature gradient
  - Electric potential (Seebeck effect)
  - Figure of merit – $ZT=\sigma S^2T/\kappa$
- Thermoelectric module
- Temperature gradient → electric potential
- N-type and p-type material
- Low efficiency
- Active cooling → high power

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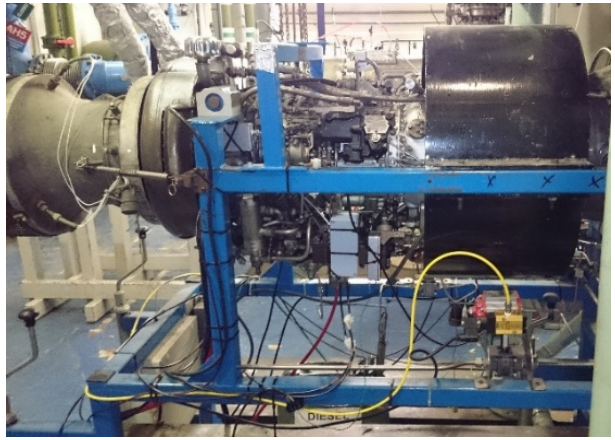
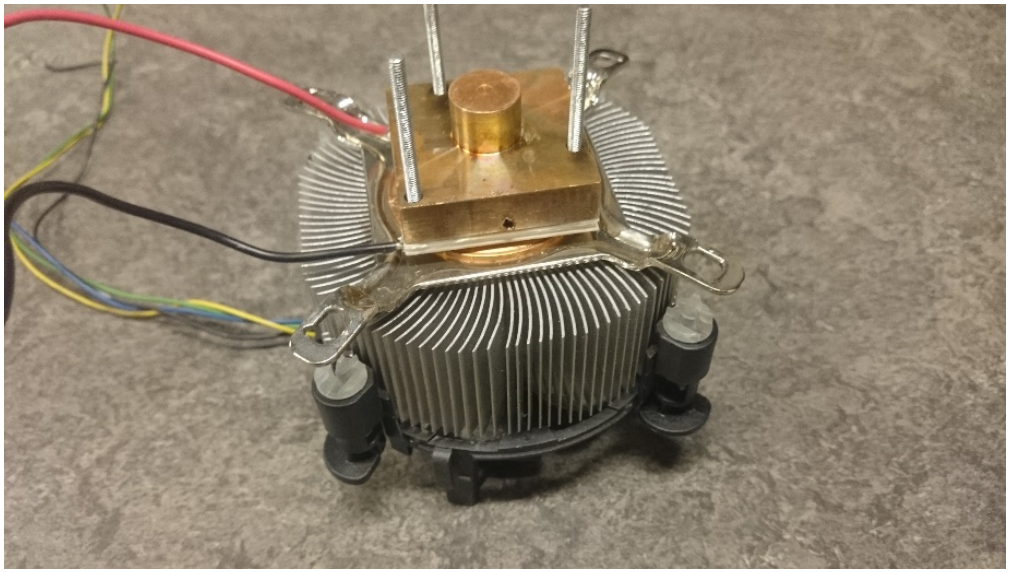
# Thermoelectric Energy Harvester

- Proof of concept harvester
  - Ex-service Rolls-Royce gas turbine



Test rig

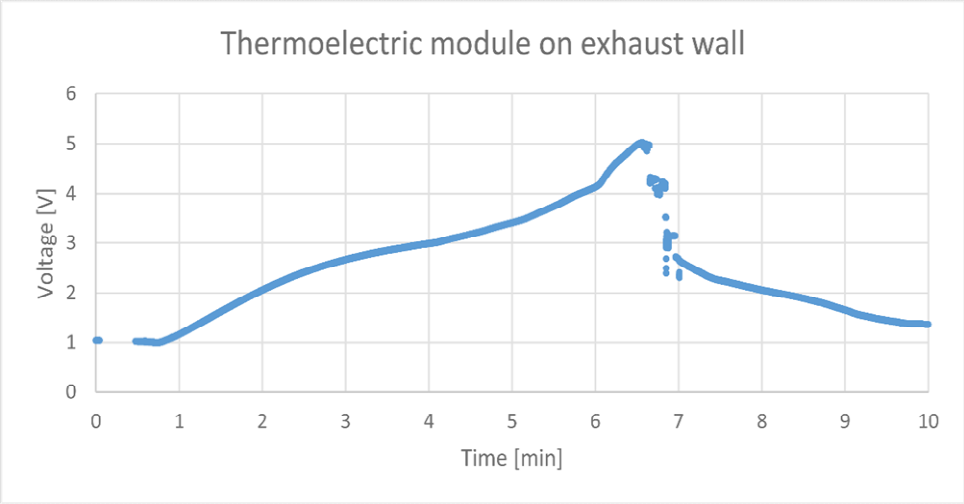


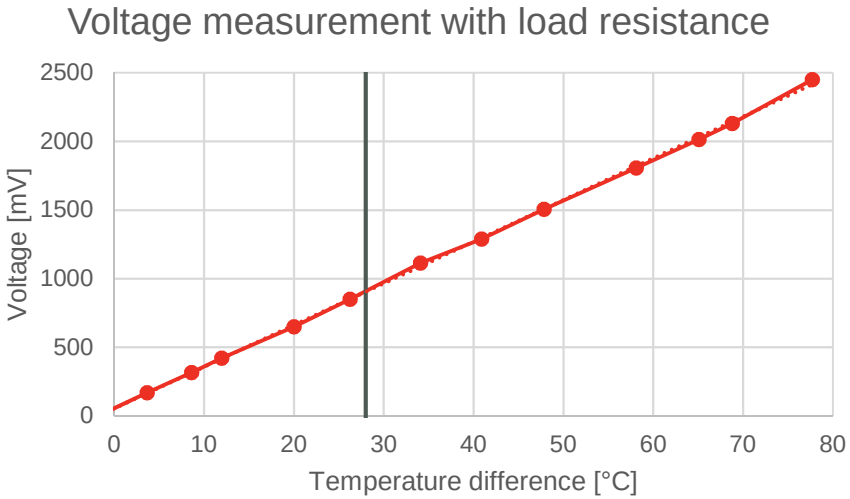
Proof of concept harvester

# Thermoelectric Energy Harvester

- Melted results
- Enough power at ΔT=28°C

Success!!!

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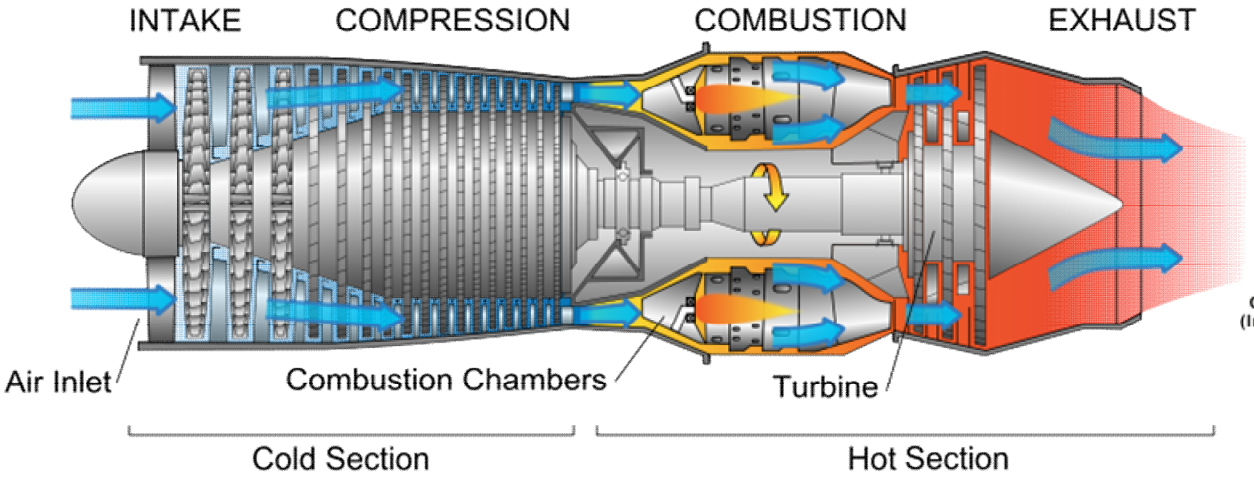
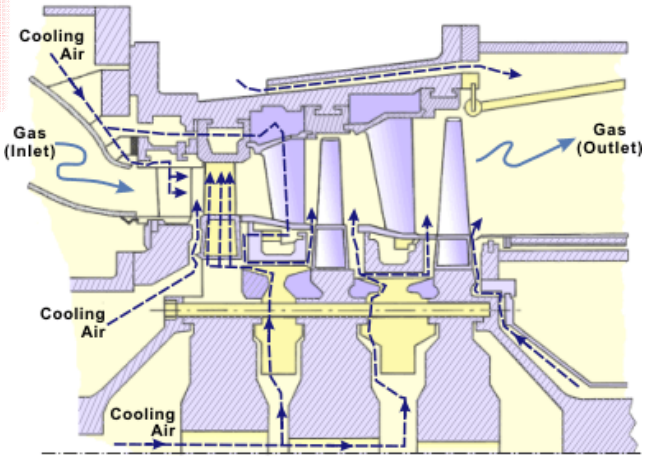
# High Temperature Thermal Harvester

- High temperature version investigated



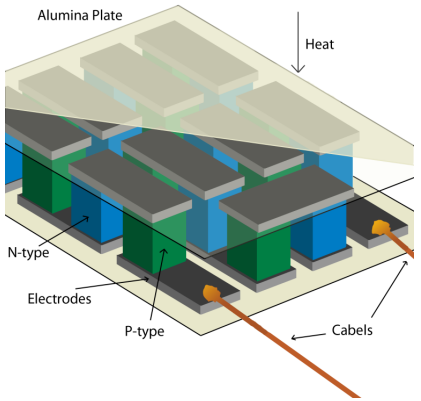




Cooling Channels

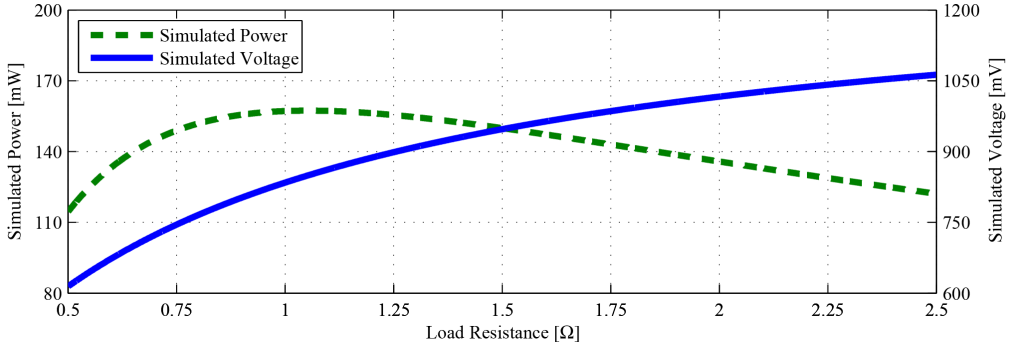
High temperature sections

- 800-1800°C hot walls
- 550-600°C cooling air

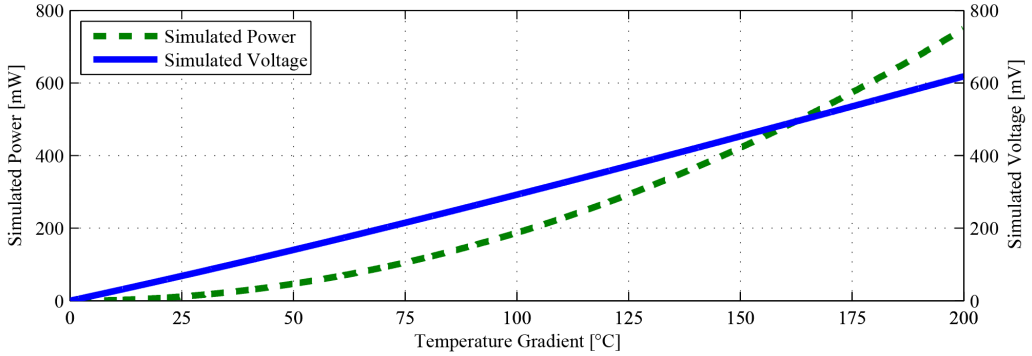
# High Temperature Thermal Harvester Design




- Small enough for cooling channels
  - 1 $cm^2$ and 0.4 g
- What materials?
  - Thermoelectric
  - Insulation
  - Electrodes
- Analytical modelling
  - Electrical conductivity
  - Thermal conductivity
  - Joule heating
  - Contact resistance
  - And more…




Simulated power and voltage with 17 couples. The cold side of the device is 600°C with 800°C on the hot side of the device. In this calculation DC-DC converter and cable losses are included.




Simulated power and voltage with 7 couples. The cold side is kept constant at 600°C with increasing hot side temperature.

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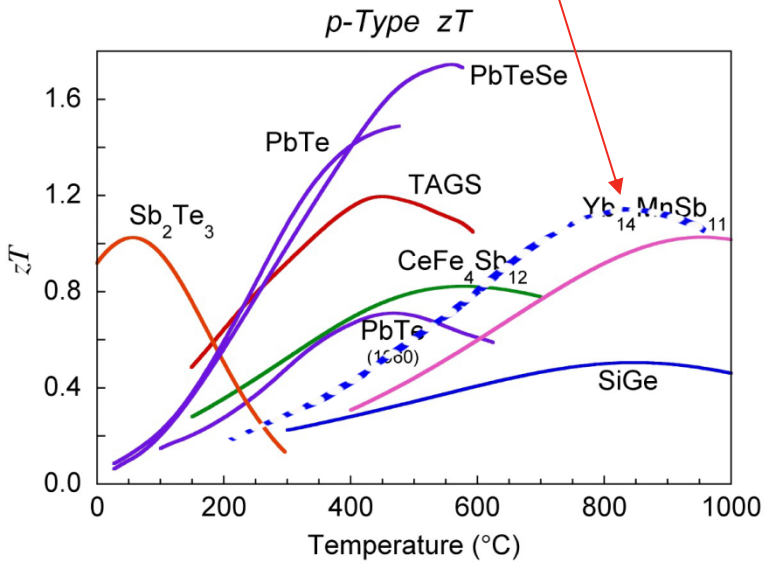
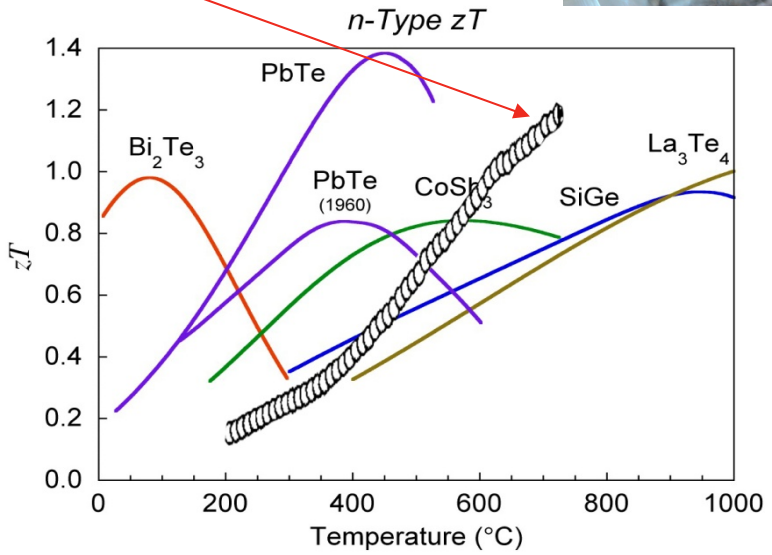
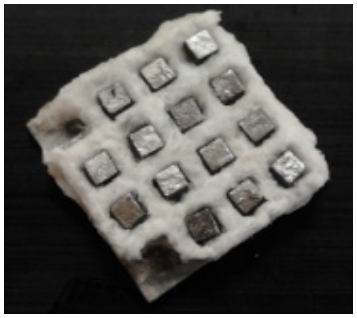
# High Temperature Thermal Harvester Thermoelectric materials

- Choice of thermoelectric material (600-800ºC)
- $Ba_8Ga_{16}Ge_{30}$ (n-type)
- $Yb_{13.6}La_{0.4}MnSb_{11}$ (p-type)



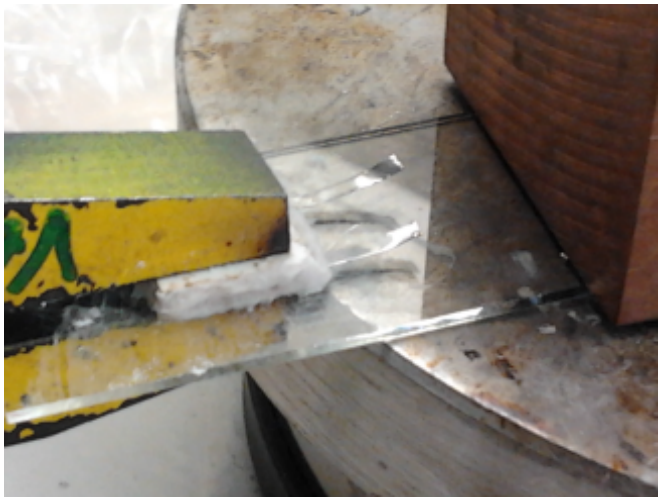



# High Temperature Thermal Harvester Materials

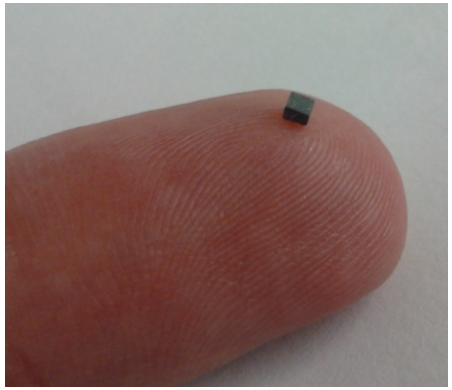


Ceramic insulating material

Molybdenum electrodes



Fabrication and sealing in glove box

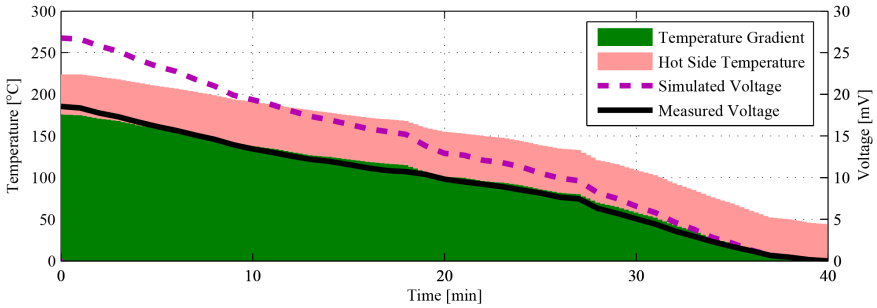


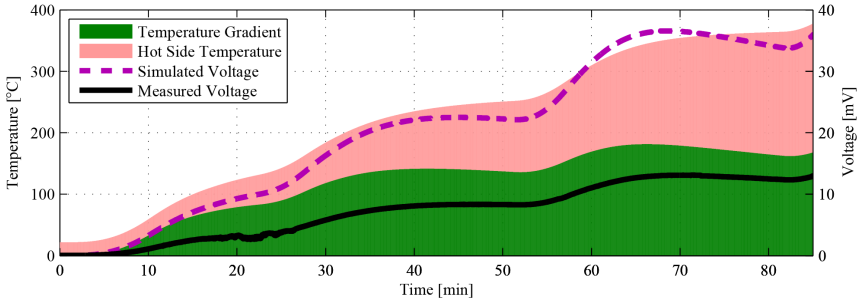
One $Ba_8Ga_{16}Ge_{30}$ leg

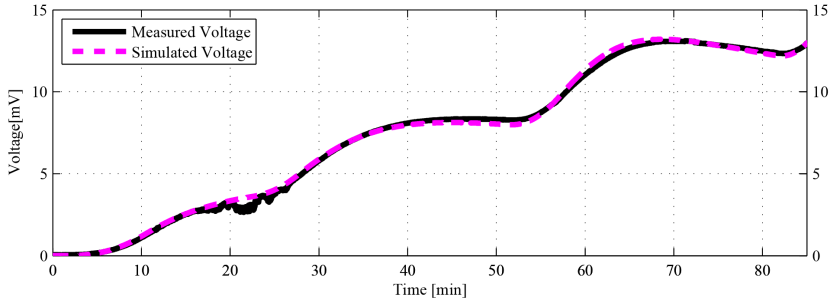
PTFE mold

# High Temperature Thermal Harvester Measurements

- Chalmers measurement
  - Close to simulations
- GKN measurement
  - Higher temperature
  - Bad thermal contact

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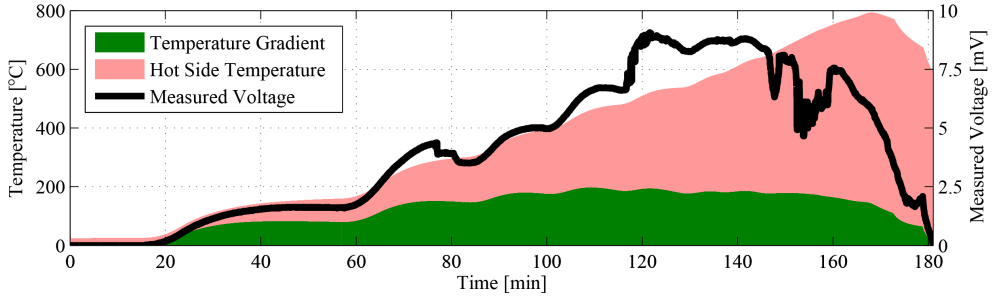
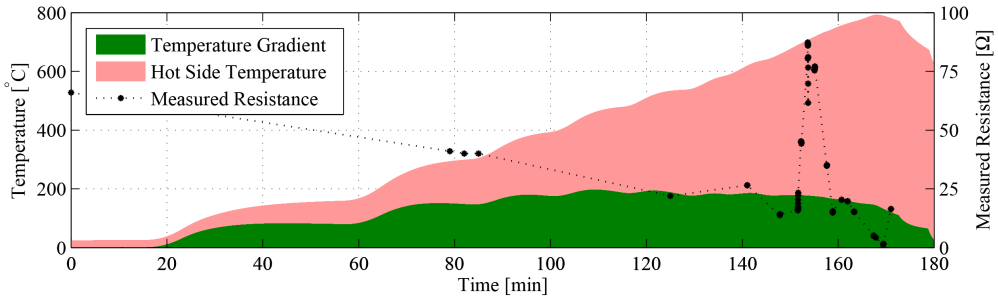
# High Temperature Thermal Harvester Measurements

- GKN furnace
  - Survived 800°C
  - Bad thermal contact
  - Internal contact bad

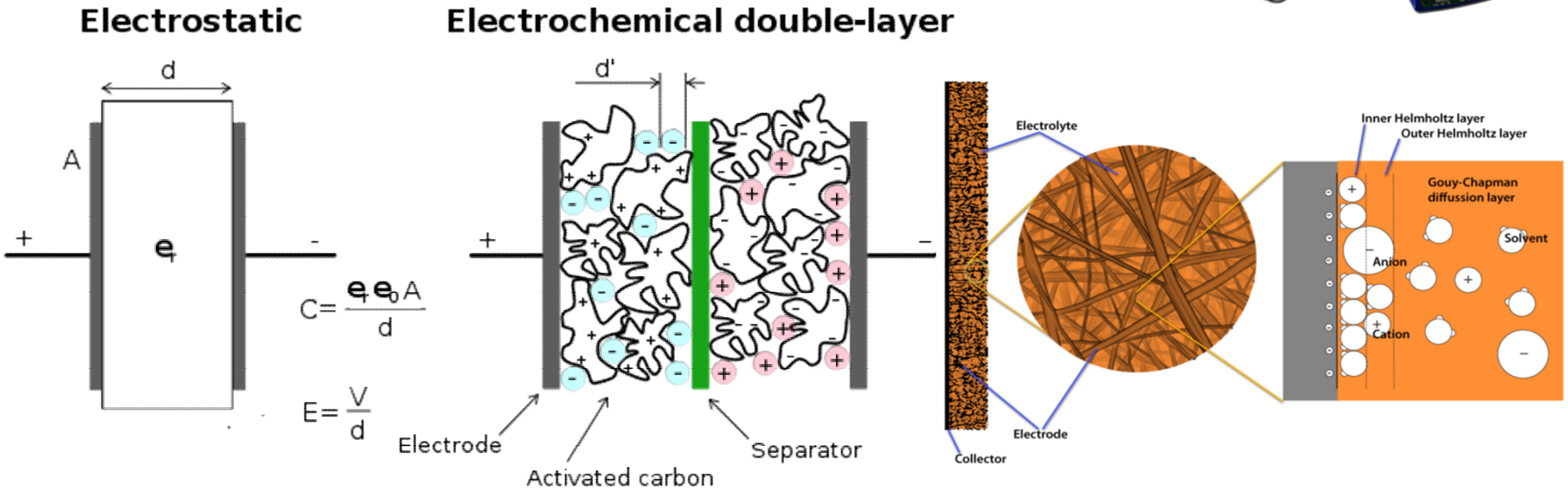


# Supercapacitors

## What is a supercapacitor?

An electric double-layer capacitor (EDLC), also known as supercapacitor, supercondenser, electrochemical double layer capacitor, or ultracapacitor, is an electrochemical capacitor with relatively high energy density.

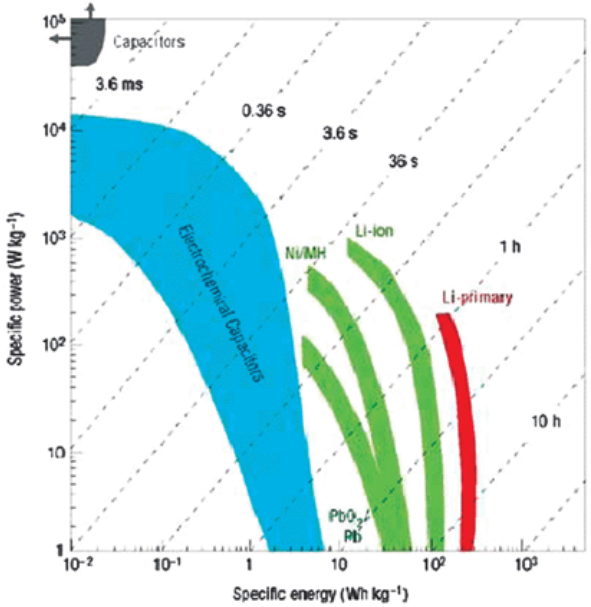
# Supercapacitors vs Batteries

**Disadvantages compared to batteries**

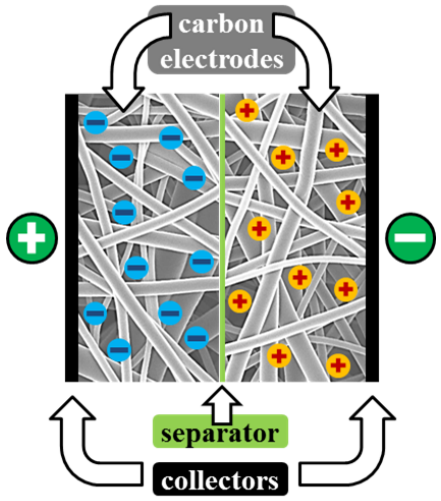
- Low electric energy density, low Wh/kg
- High self discharge, discharges when not used
- Low max voltage, for commercial electrolytes
- Voltage drop during discharge

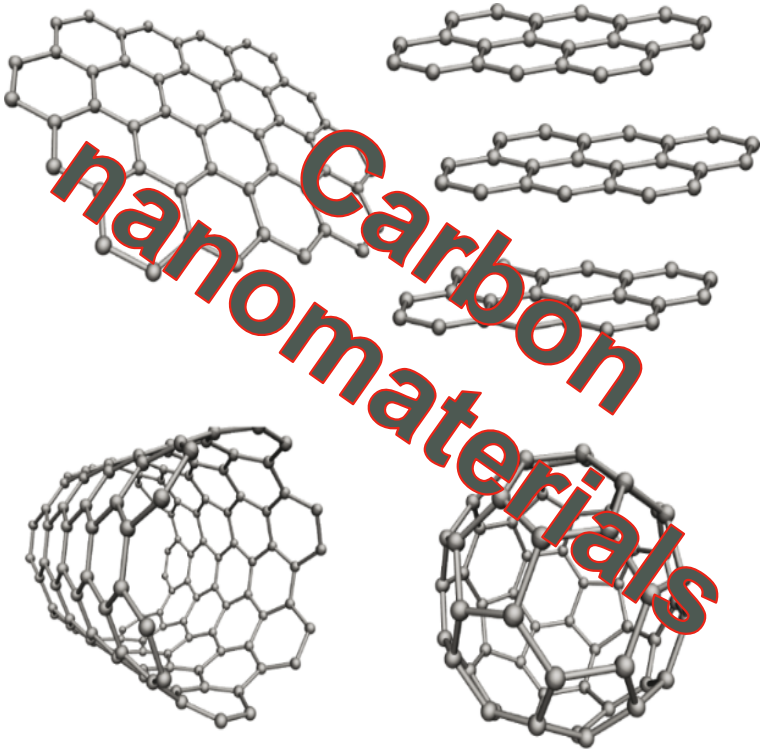
**Advantages compared to batteries**

- Long life, Low cost *per cycle*
- Very high rates of charge and discharge
- Extremely low internal resistance, means low heating levels
- High output power
- Improved safety, no corrosive electrolyte and low toxicity of materials



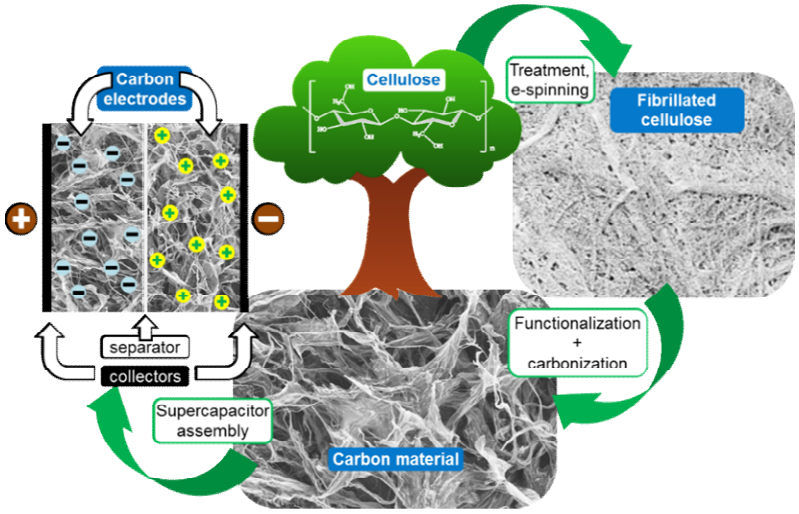
# Supercapacitor Electrode material



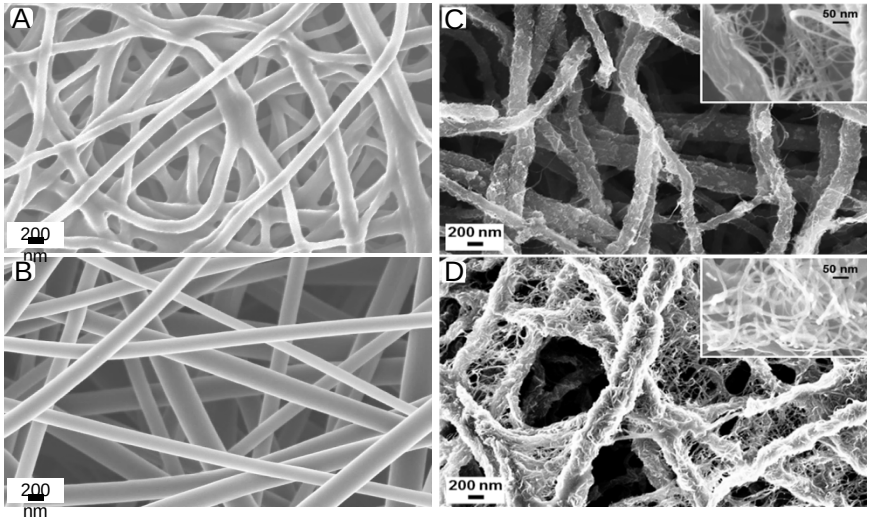




- Electrical conductivity
- Surface area
- Hierarchical porosity
- Mechanical stability
- Electrochemical stability
- Sustainability

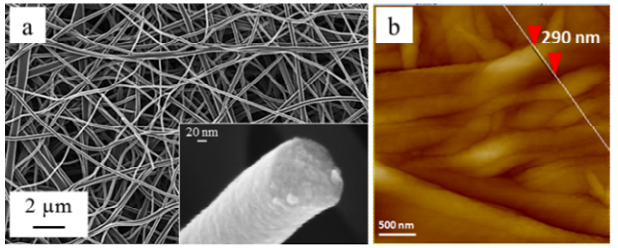
# Supercapacitor Electrode material




| Sample | Nitrogen content [%] | Specific surface area [m²/g] | Electrical conductivity [S/cm] | Specific capacitance [F/g] |
|---|---|---|---|---|
| Pure CNFs | - | 45 | 4.5 | 46 |
| N-doped CNFs | 4.0 | 25 | 10.2 | 58 |
| CNFs + DWCNTs | - | 60 | 85.3 | 163 |
| CNFs + MWCNTs | - | 168 | 98.2 | 241 |




SEM images of electrode materials: pure CNFs (A), N-doped CNFs (NCNF) (B), CNFs functionalized with DWCNTs (C) and MWCNTs (CNF/MWCNT) (D)




a. SEM images of the CNFs synthesized from regenerated cellulose;
b. AFM image of the same CNFs



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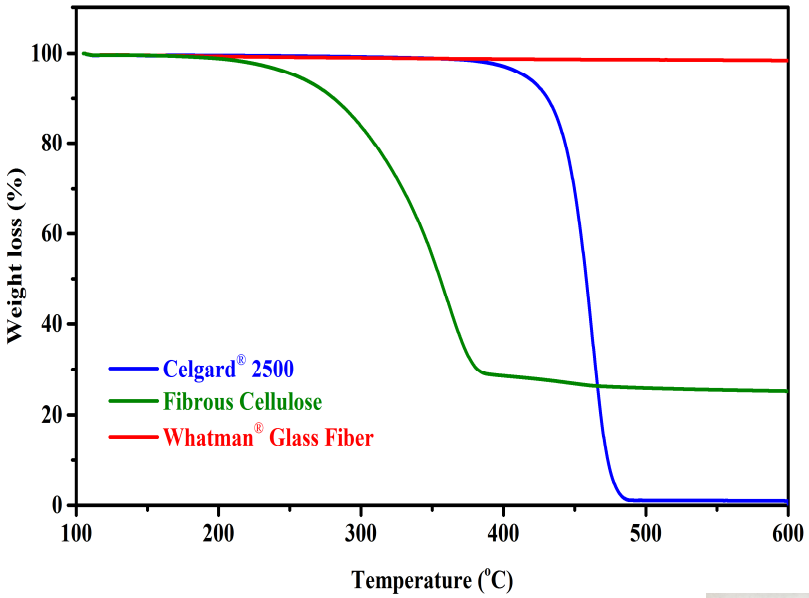
# High temperature supercapacitor Separators




Whatman® glass fiber

Celgard® 2500

Fibrous cellulose

**Major considerations for separator selection**

- Thermal stability: for high temperature
- Mechanical property: for convenience of manual assembly
- Affinity to electrolytes

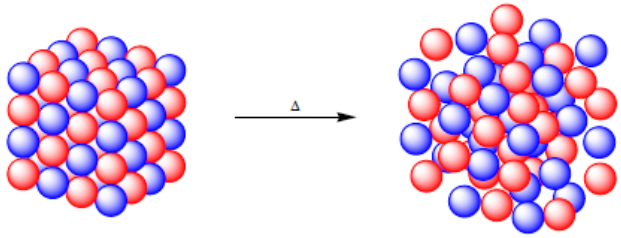
# High temperature supercapacitor Electrolyte

**Aqueous electrolyte**

- Good ion mobility
- Low voltage, 1 V due to the water electrolyses
- Lower maximum temperature

**Nonaqueous electrolyte**

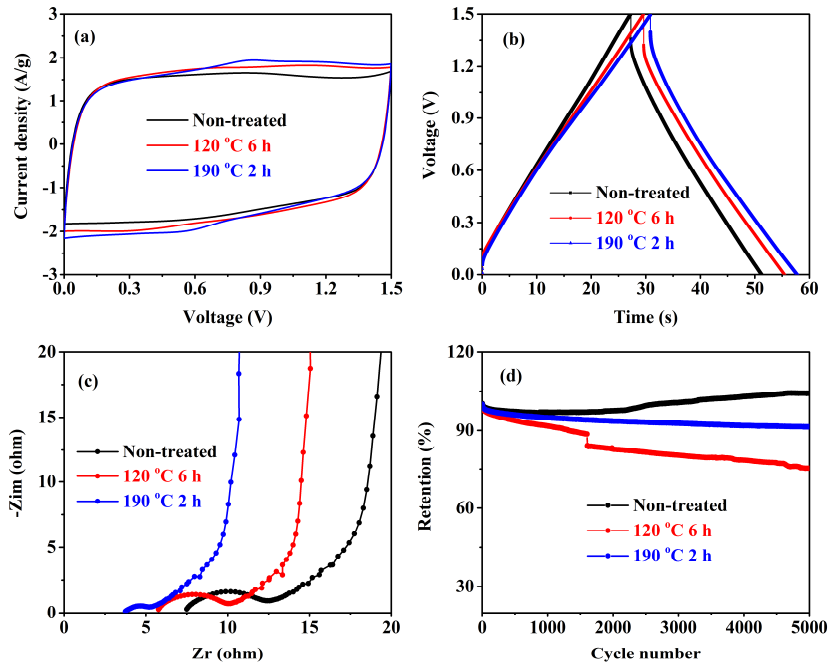
- Aprotic solvents 2,5 V
  - High cost
  - Low ion mobility
  - Low dielectric constant (low capacitance)
- Ion liquids (room temperature molten salts) >3 V
  - Non-toxicity
  - Non-flammable
  - High viscosity
  - Low ion mobility at room temperature
  - When you heat a salt it will melt (e.g. NaCl, 801 ºC, CaCl 776 ºC)



# High temperature supercapacitor Electrolyte

## Non-aqueous (EMIm Ac)

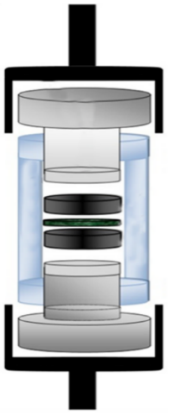
**Treated at 120 ºC, 6 h or 190 ºC, 2 h**




**Notes for EMIm Ac**

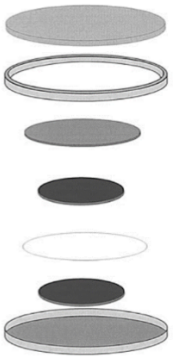
- Specific capacitance increases with temperature treatment (non-treated, 73 F/g ➔ 120 ºC, 79 F/g ➔ 190 ºC, 81 F/g).
- Cycling stability decreased after treatment (non-treated, 100+% ➔ 120 ºC, 75% ➔ 190 ºC, 91%)
- Treatment duration may play a more important role than temperature.

# High temperature supercapacitor Packaging



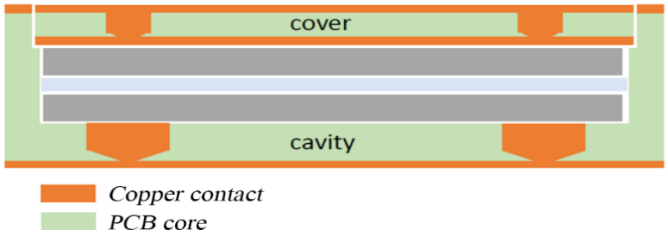
(a) Swagelok cell

*Cap (stainless steel)*
*Current collector (stainless steel)*
*Electrode pellet*
*Separator/Gel electrolyte*
*Electrode pellet*
*Current collector (stainless steel)*
*Cap (stainless steel)*



(b) Coin cell

*Casing top (stainless steel)*
*Gasket*
*Spacer (stainless steel)*
*Electrode pellet*
*Separator/Gel electrolyte*
*Electrode pellet*
*Casing bottom (stainless steel)*




(c) FR4 supercapacitor

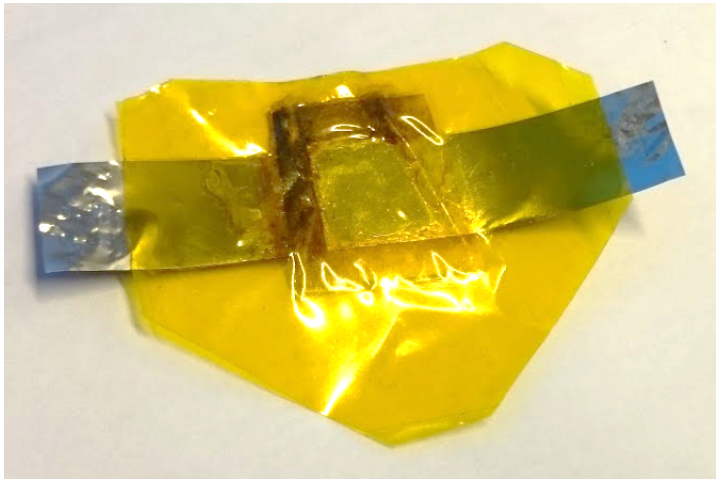
*Cover*
*Electrode sheet*
*Separator/Gel electrolyte*
*Electrode sheet*
*Cavity*

(d) Kapton tape

# High temperature supercapacitor Measurements

**Glassfiber as membrane**

**CNF as electrode**



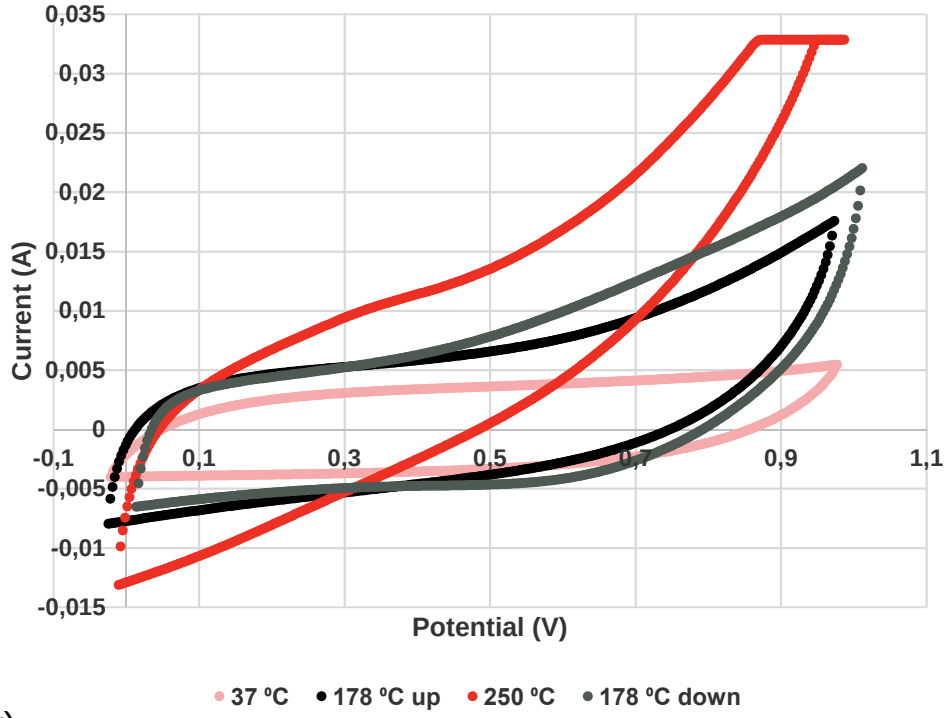
**Electrolyte**

- 1-Ethyl-3-methylimidazolium acetate (EMImAc)
  - 100 ºC melting point
  - 180 ºC boiling point
- Electrolyte for 250-500 ºC : 60% $CaNO_3$ and 40% $KNO_3$ (to be tested)

# High temperature supercapacitor Measurements

## Increased energy density with increased temperature

Measurement setup (flexible supercapacitor)



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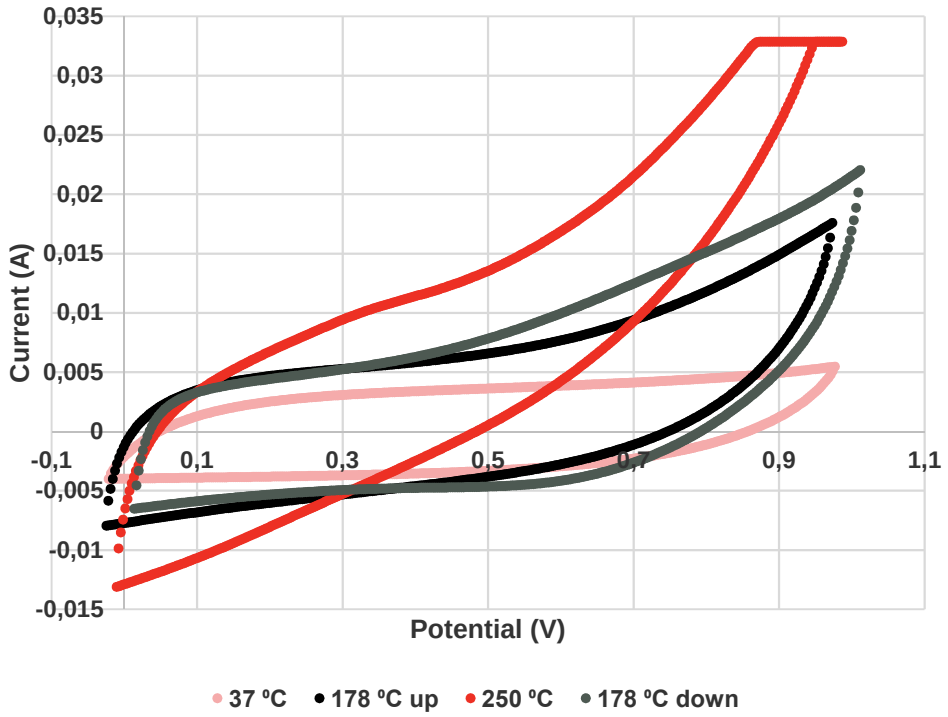
# High temperature supercapacitor Measurements

## Increased energy density with increased temperature

| Temperature (°C) | Capacitance (mF) |
|---|---|
| 37 | 57 |
| 178 (up) | 92 |
| 250 | 194 |
| 178 (down) | 100 |



# Conclusions

## Conclusions piezoelectric harvester

- Broader bandwidth and higher output is achieved by coupled cantilevers
- Passive self-tuning gives broader bandwidth
- The harvester is not sensitive to temperatures up to 100°C
- Coupled harvesters yield enough energy to power an IWS

## Conclusions thermoelectric harvester

- Successful proof of concept energy harvester
  - Powered one sensor with excess heat from gas turbine (Could power 30 sensors)
  - Operating temperature too low
- High temperature module
  - Fabrication of a 1-couple prototype
  - Wi-Fi start-up with high temperature harvester?
    - Possibly at 160°C gradient with 1 $cm^2$ module (0.4 gram)

## Conclusions supercapacitor high temperature energy storage

- Separator Glassfiber suitable
- CNF as electrode (sustainable from cellulose)
- Electrolyte 1-Ethyl-3-methylimidazolium acetate (EMImAc)
- **Increased energy density at elevated temperatures**

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# Acknowlegdement


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  - Stargate
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- Swedish Energy Agency
- Wallenberg Wood Science Centre
- Swedish Research Council

# Thank You for Your Attention!

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