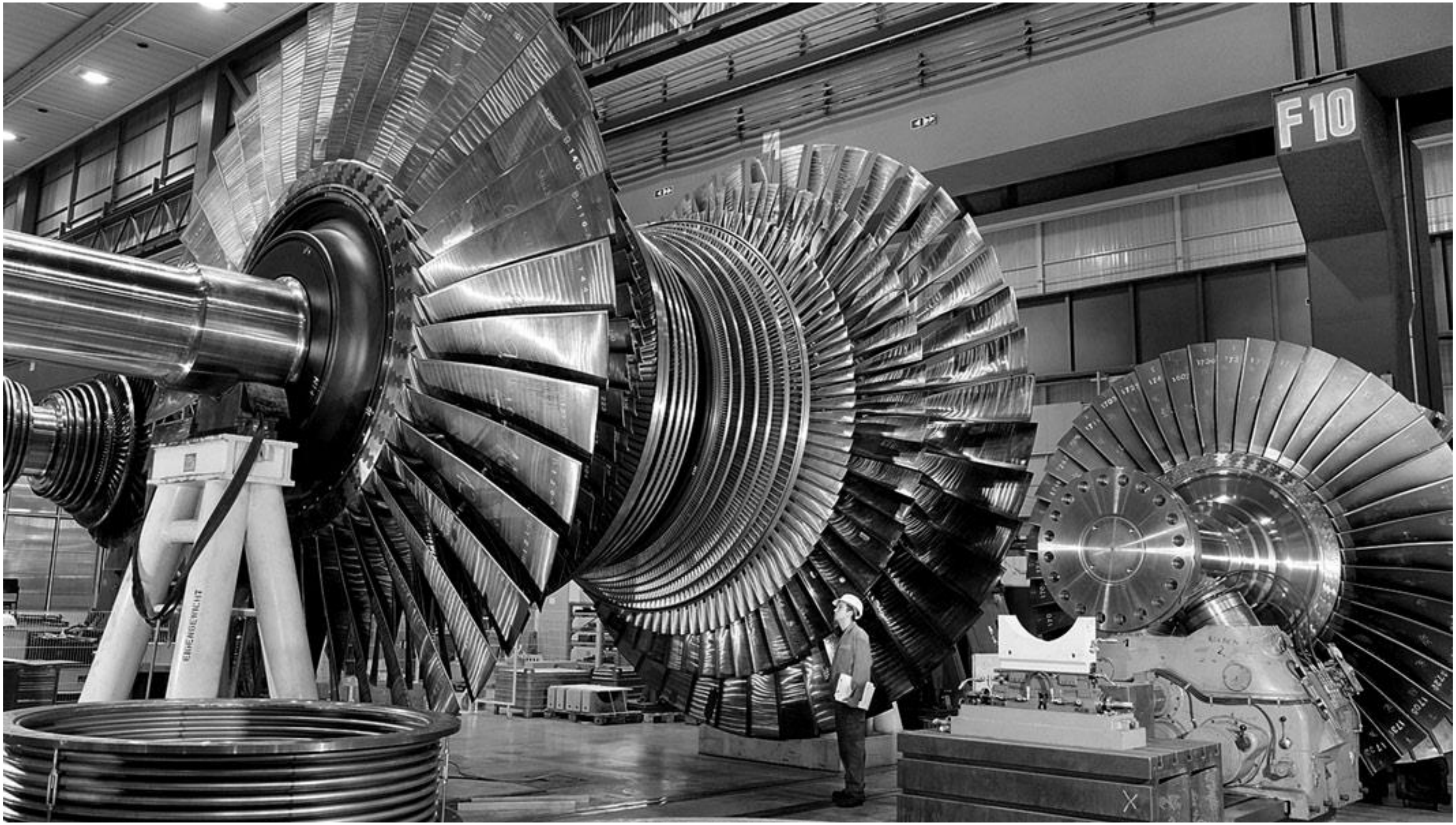


Applications of piezoceramic thick films

E. Ringgaard, T. Zawada, K. Astafiev, M. Guizzetti, L.M. Borregaard, R. Xu, K. Elkjaer and W.W. Wolny

CIMTEC 2014

12 June 2014

Outline

1 Company introduction

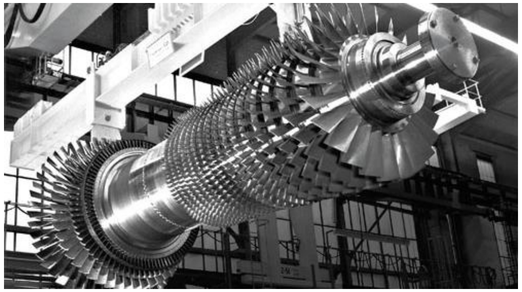
2 Piezoceramic thick films

3 Flexible piezoelectric films – PiezoPaint™

4 Applications of piezoelectric films

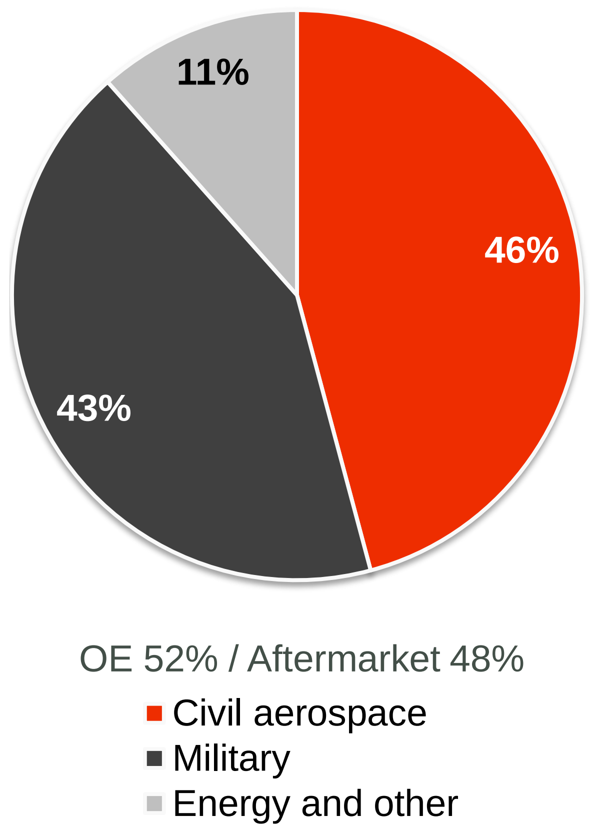
5 Conclusion

1 Company introduction



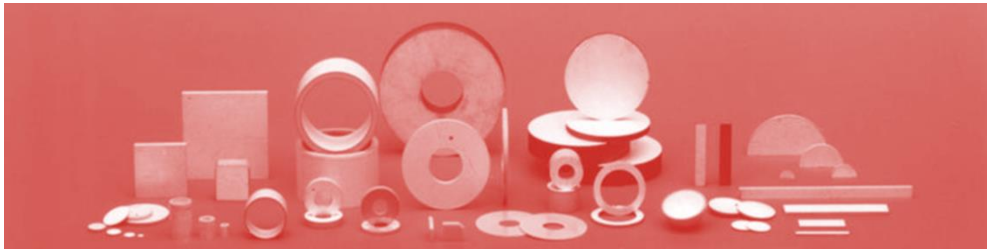
Overview

- Provides high technology products and systems for the aerospace, defence and other specialised markets, e.g. medical, industrial, energy, test and automotive
- 60 years experience in extreme environment engineering
- Annual sales (2012), £1.6 billion
- Listed on London Stock Exchange (in FTSE100)

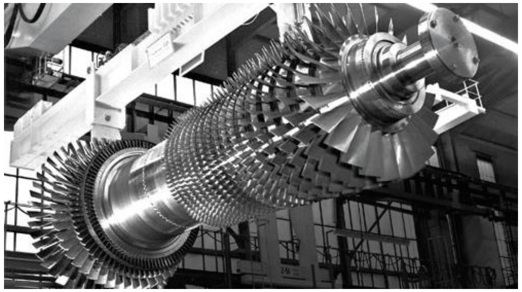


CTS | Ferroperm Denmark

- We are a manufacturer of piezoelectric materials, components and devices under the trademarks Ferroperm™ and InSensor™
- 2-3 million units produced annually
- Major markets
  - Medical ultrasound
  - Underwater acoustics
  - Acceleration sensors
  - Flowmeters
  - Energy harvesting

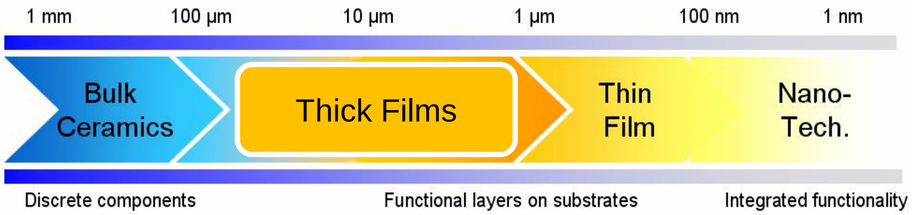


2 Piezoceramic thick films for integrated devices



PZT thick films – InSensor™

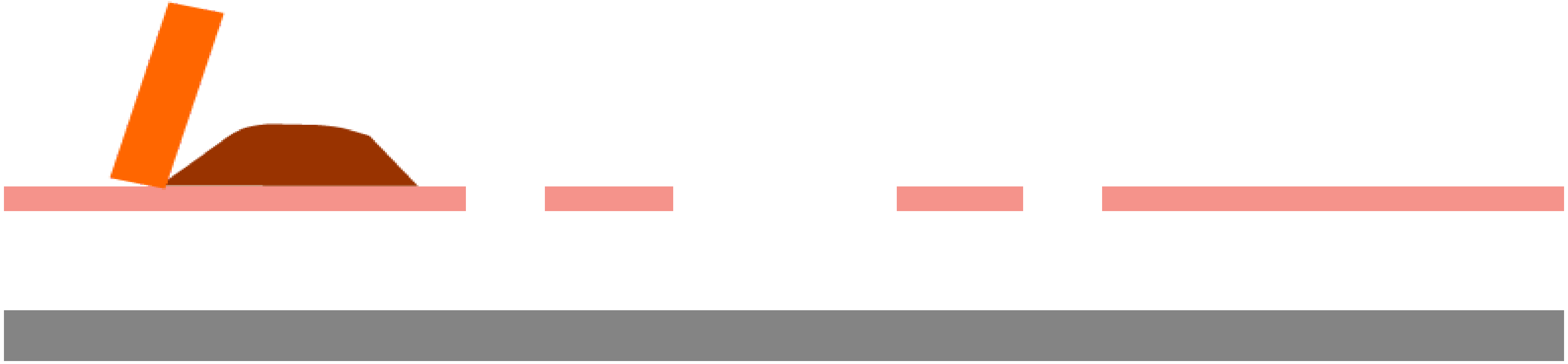
- Technology of piezoelectric thick films – enabling deposition and integration of piezoelectric layers (10 µm to 100 µm in thickness) with high lateral resolution (100 µm x 100 µm)



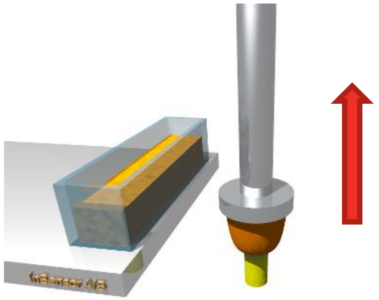
- Key features of InSensor™ technology
  - Capable of manufacturing miniaturized devices
  - Low prototyping costs
  - High volume production
  - High lateral resolution
  - High frequency
  - High response
  - Piezoelectric material can be deposited on a number of different substrates (compatible with MEMS)

Deposition – screen printing

Paste: PZT powder dispersed
in an organic vehicle

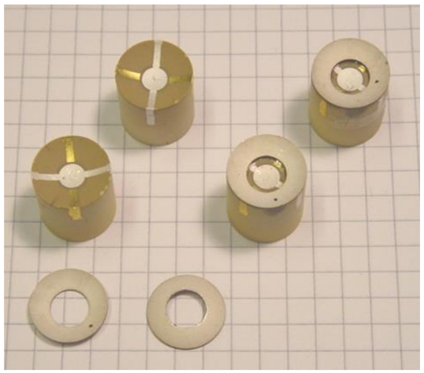


Deposition – pad printing



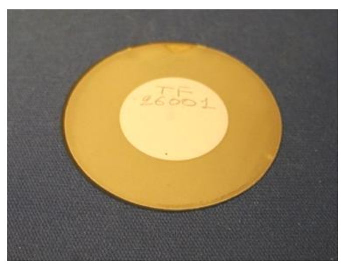
PZT thick film compatibility

SUBSTRATES

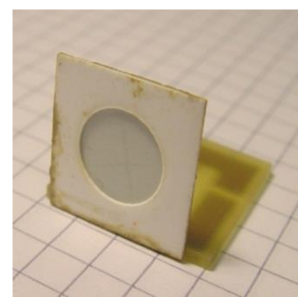


Ceramics

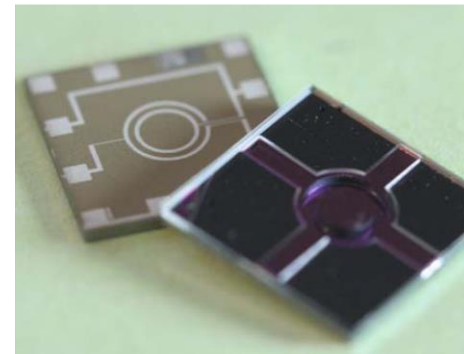
[A. Guiroy et al., IEEE UFFC **60** 2634 (2013)]



Stainless steel



LTCC



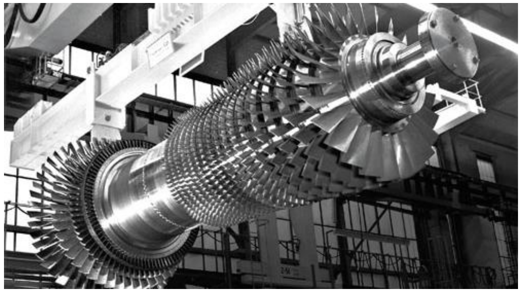
Silicon

Evolution in screen printing of piezoelectric materials

Substrate	Processing temperature
» Ceramic (e.g. alumina, PZT)	» 1100 ºC – 1250 ºC
» Steel, silicon, ceramic, LTCC	» 800 ºC – 900 ºC (InSensor™)
» Polymer	» 150 ºC (PiezoPaint™)
» Textile	» 100 ºC
» Paper	» 100 ºC or less

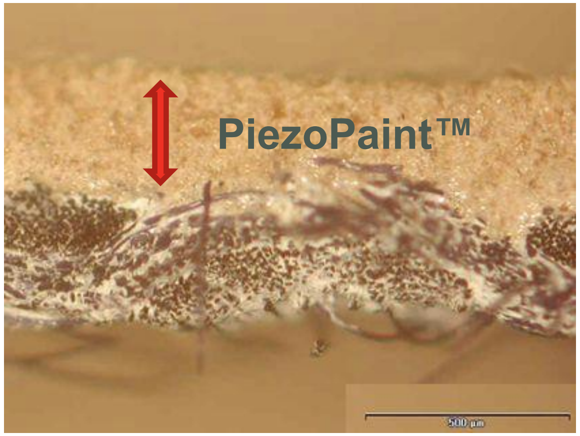
PROCESSING TEMPERATURE

3 Flexible piezoelectric materials – PiezoPaint™



Flexible piezoelectric film – PiezoPaint™

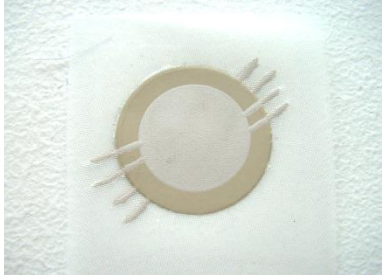
- Ultralow-temperature processing piezoelectric material, $T < 150$ ºC
- High response ($d_{33} > 45$ pC/N) compared to piezoelectric polymers
- The outstanding properties make the material very attractive for several application
  - Sensors
  - Transducers
  - Actuators
- Patent registered: 2608287-EPO



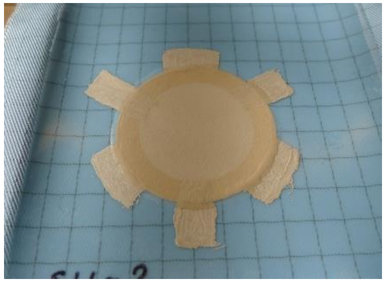
PiezoPaint™ – choice of substrates

- Fabrics
- Textiles
- Composites
- Metals
- Plastics/polymers
- Laminates
- Ceramics
- Paper
- PCB
- etc.

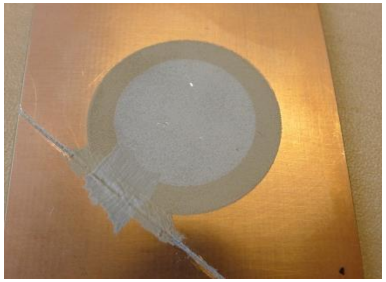
PiezoPaint™ on polymer



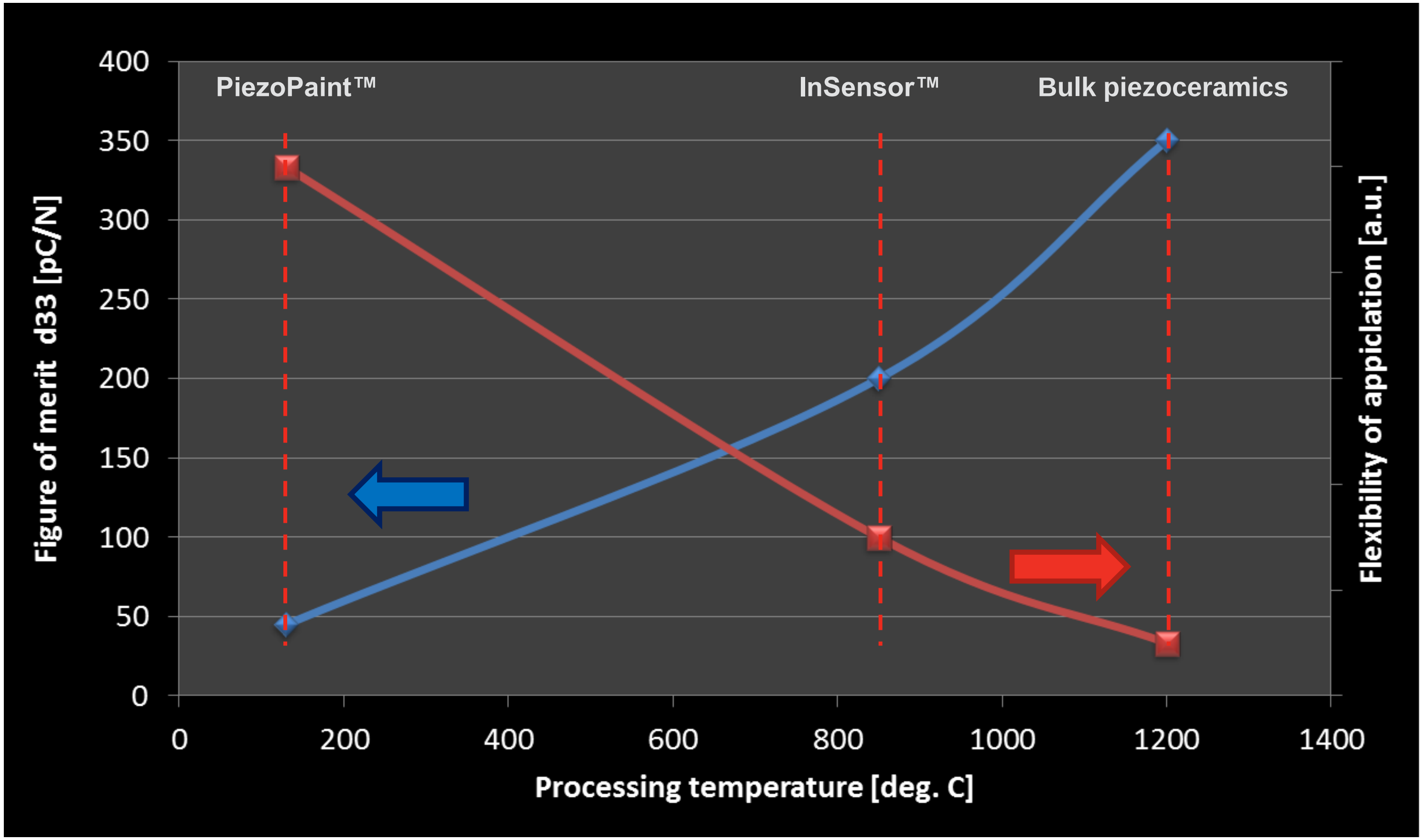
PiezoPaint™ on fabric



PiezoPaint™ on PCB

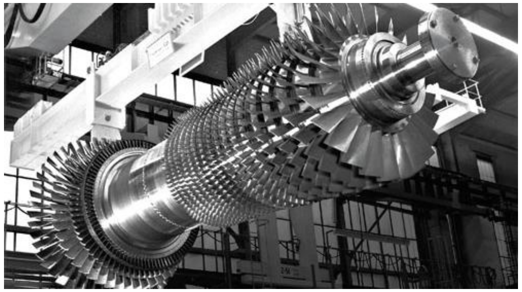


Piezoelectric films – summary



InSensor™ and PiezoPaint™ are trademarks of CTS | Ferroperm

4 Applications of piezoelectric films



Application examples

1 | **Structural health monitoring**

2 | Energy harvesting

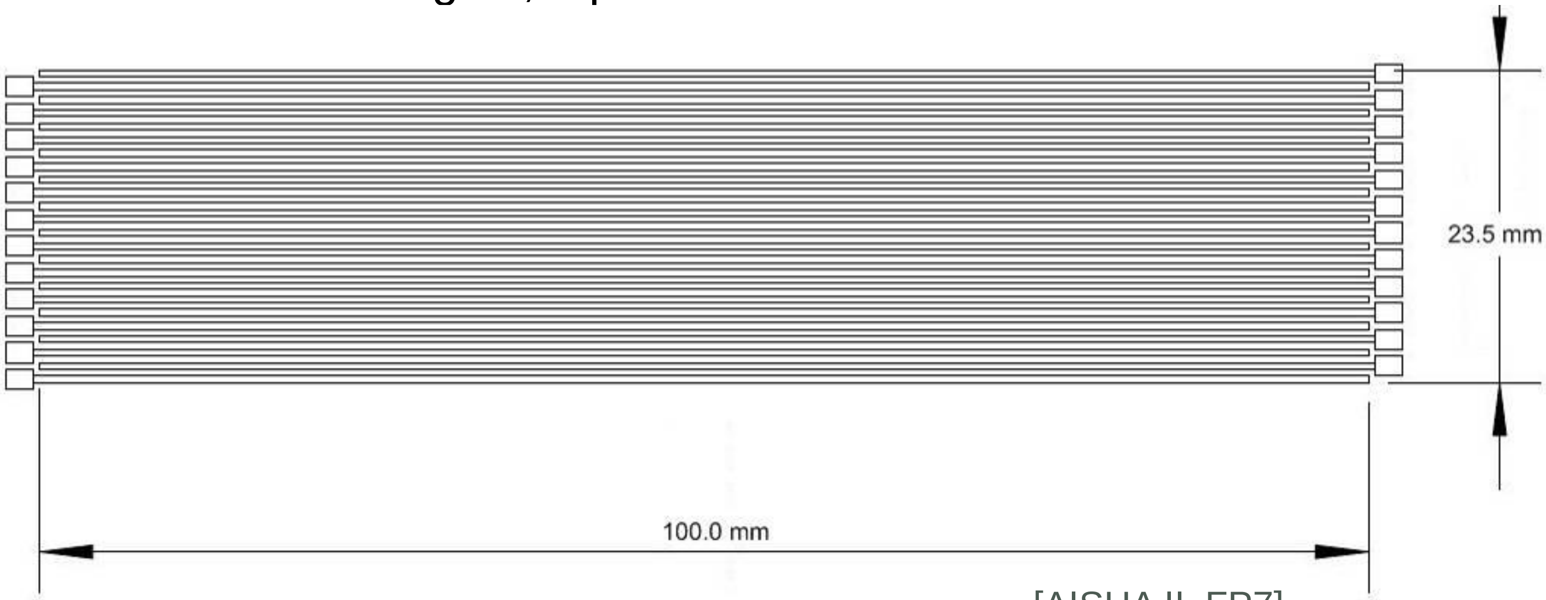
3 | Medical imaging

4 | Impact detection

5 | Motion sensor

Structural health monitoring: multi-element thick-film arrays for Lamb wave generation

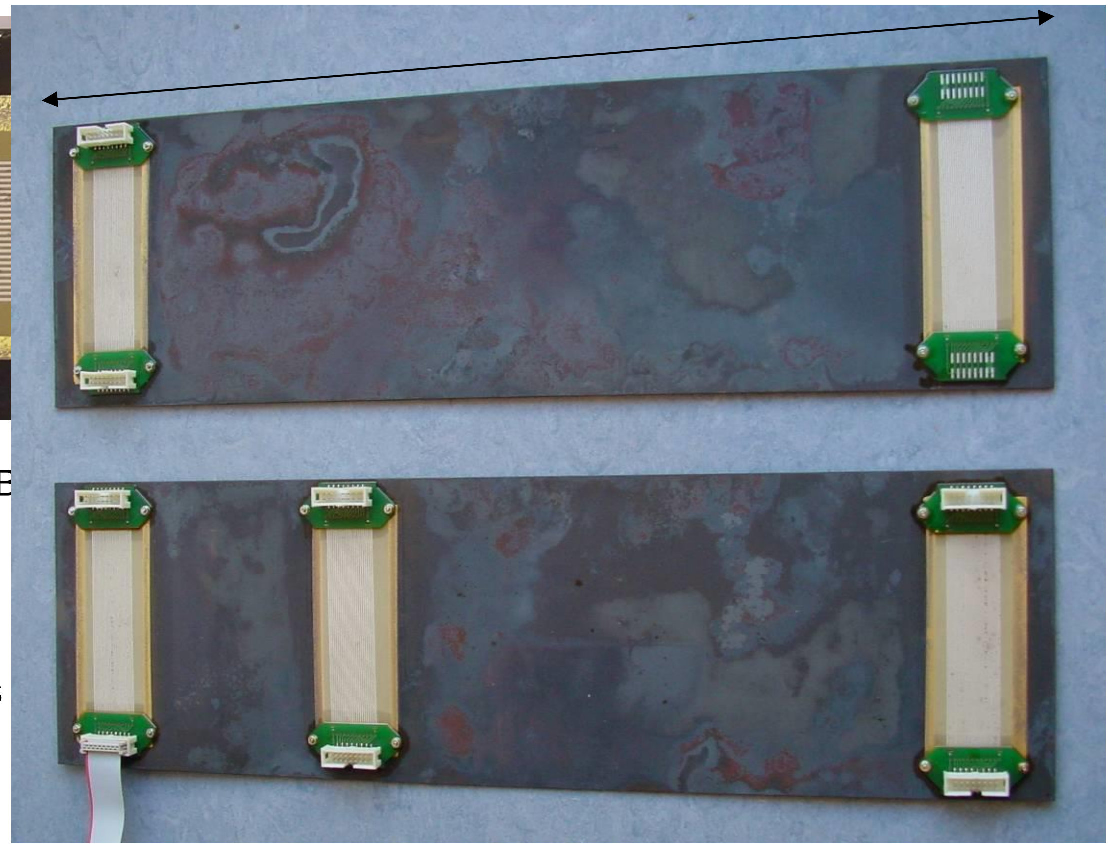
- Number of elements: 24 (linear array)
- Substrate: stainless steel
- Thick film: PZT-based, $h < 100\ \mu m$
- Electrodes: bottom gold, top silver



[AISHA II, FP7]

Mounting of connector

500 mm



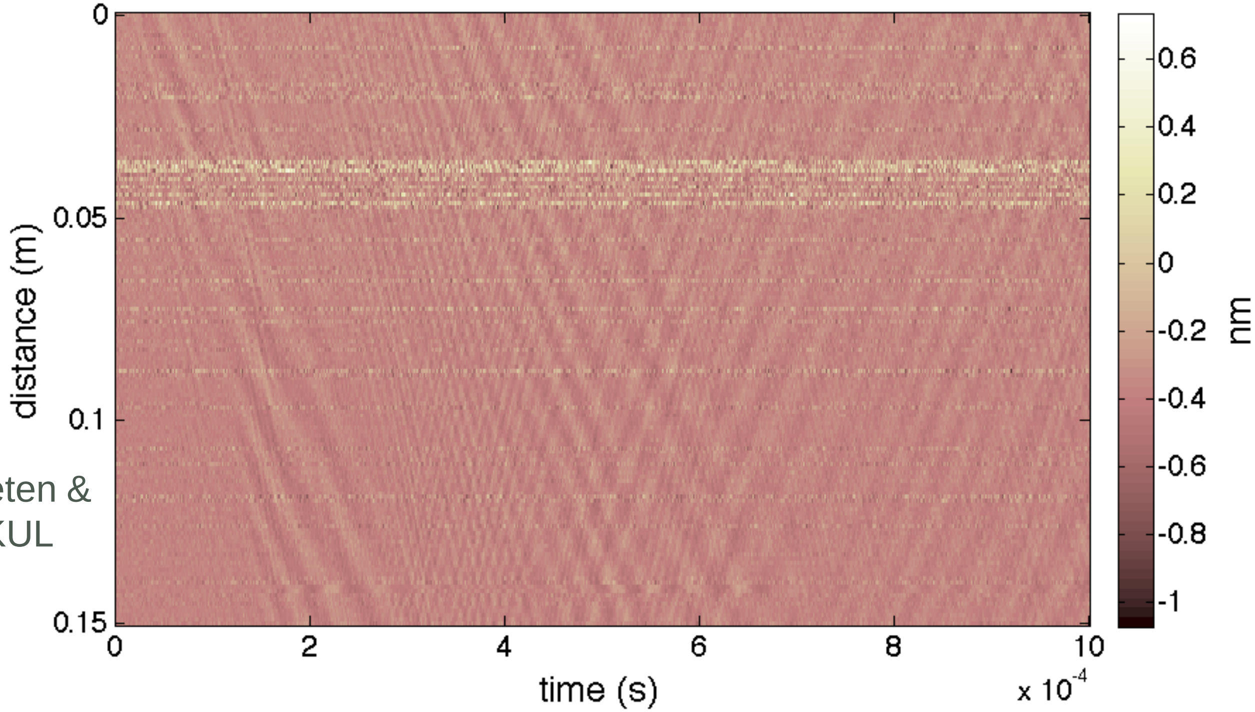
Thick-film array with PCB

The two transmission lines with connectors mounted on all 5 arrays

Lamb mode selection

Displacement measured by Doppler vibrometer

» 8 array elements selected to form a wave with λ = 20 mm (f_{excit} 267 kHz)



Measmt. by S. Creten & C. Glorieux, ATF-KUL

Application examples

1 | Structural health monitoring

2 | **Energy harvesting**

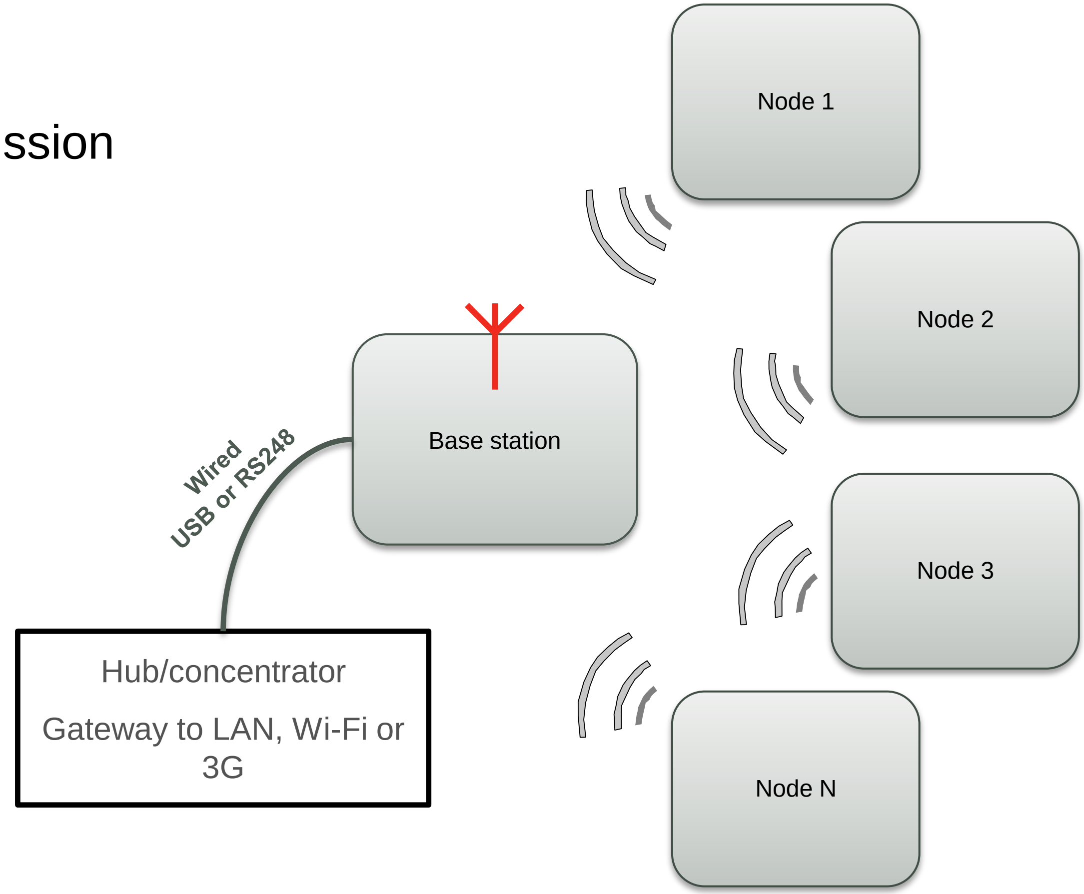
3 | Medical imaging

4 | Impact detection

5 | Motion sensor

Energy harvesting based wireless sensor network

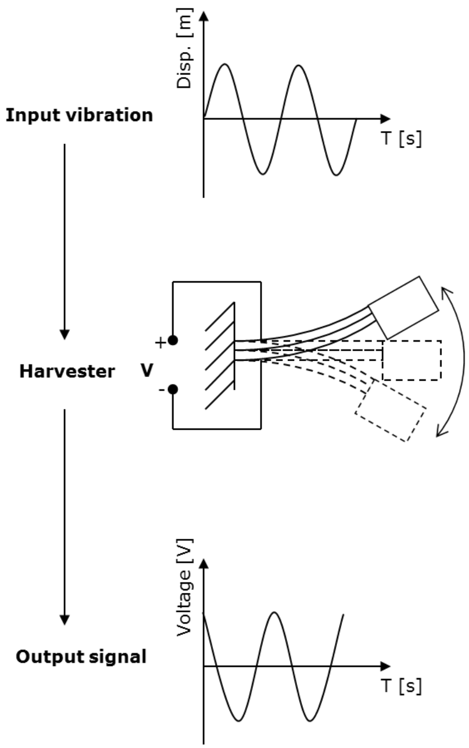
- Star topology
- Unidirectional transmission
- 16 sensor nodes
- 2.4 GHz radio link
- Proprietary protocol
- Distance (3-10 m)



Kinetic energy harvesting – basic principle

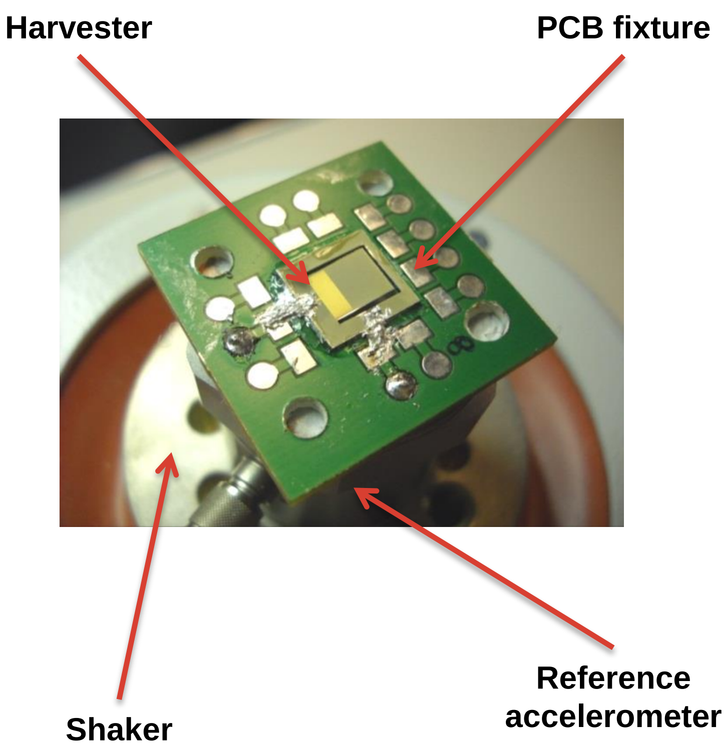
Energy Harvesting – transforming low grade energy into usable electrical energy enabling an autonomous, wireless operation of electronic devices

- The kinetic energy is transformed into electrical energy
- The kinetic energy can be in the form of the following:
  - Harmonic vibration
  - Non-harmonic vibration
  - Acoustic wave
  - Displacement
  - Rotation
  - Torque
  - etc.



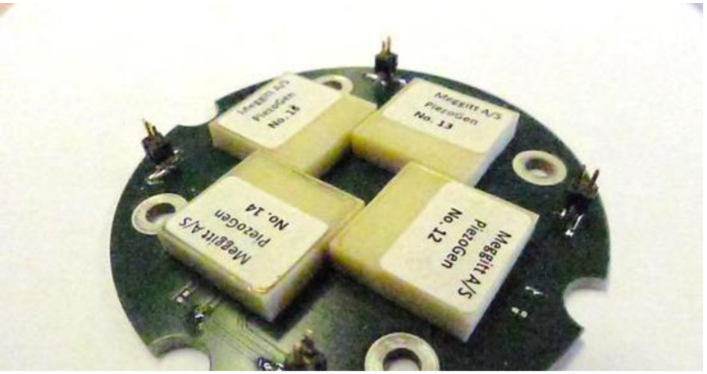
Characterization of harvesters (previous generation)

- Charge sensitivity up to 37 nC/g @ 0.5 g peak
- Open-circuit voltage up to
  - 3 V @ 0.5 g peak (unimorph)
  - **4 V @ 0.5 g peak (bimorph)**
- Maximum power range
  - 12 µW ÷ 16 µW @ 0.5 g peak (unimorph)
  - **16 µW ÷ 20 µW @ 0.5 g peak (bimorph)**
- Frequency range (tunable): 100 – 1000 Hz



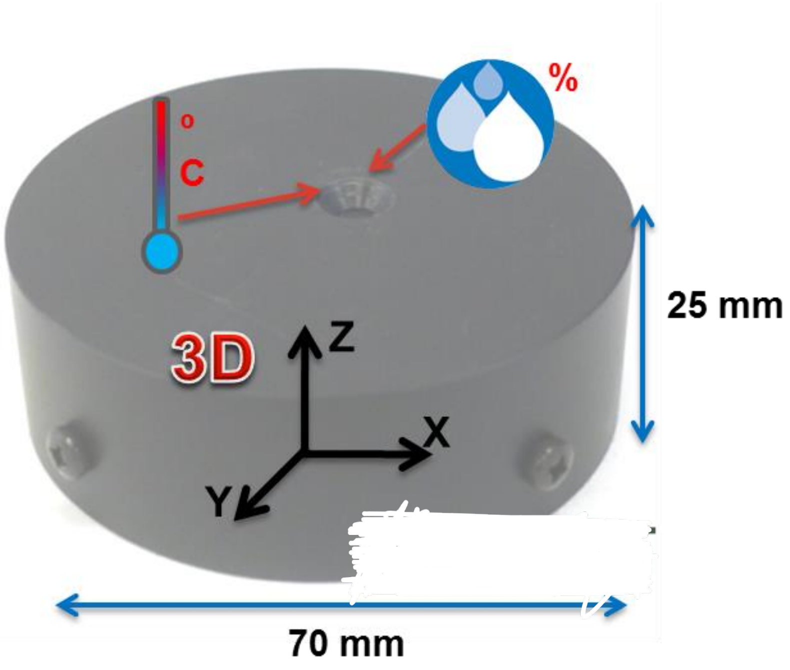
Fully assembled generator board

- Four EH devices are combined in order to assure the proper power level and bandwidth
- Fully assembled board delivers approx. 100 µW of continuous power at 0.3 *g* RMS, resonance (e.g. 300 Hz)



Sensor node

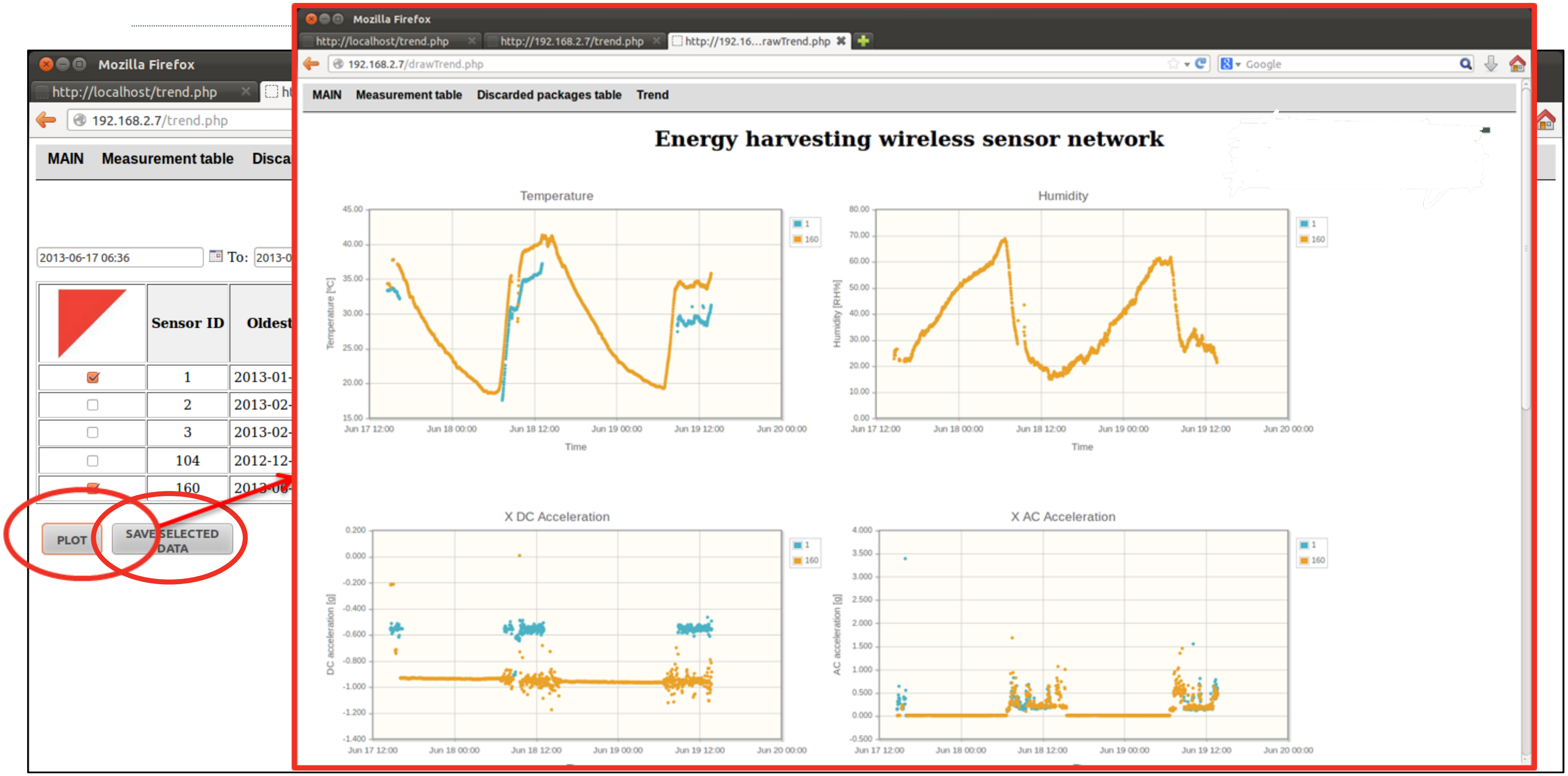
- Operation temperature
  - Range: -40 – 70 ºC
- Acceleration measurement
  - 3D acceleration measurement
  - Sampling frequency: up to 3200 Hz
  - Resolution: 13 bits
- Ambient temperature
  - Accuracy: ±0.4 ºC (10 ºC - 60ºC)
- Relative humidity
  - Accuracy: ±3.0 %RH (20% - 80%)
- Sensor nodes are linked using 2.4 GHz wireless communication in a star-like network architecture



Industrial environment setup – an example

- Energy harvesting powered sensors have been placed on hydraulic pumps located outside of the factory building
- The base station together with the data server was placed inside the factory building
- Operating harvesting frequency was 220 Hz
- Battery powered sensor node was used as the reference

Results – example of data trends



Application examples

1 | Structural health monitoring

2 | Energy harvesting

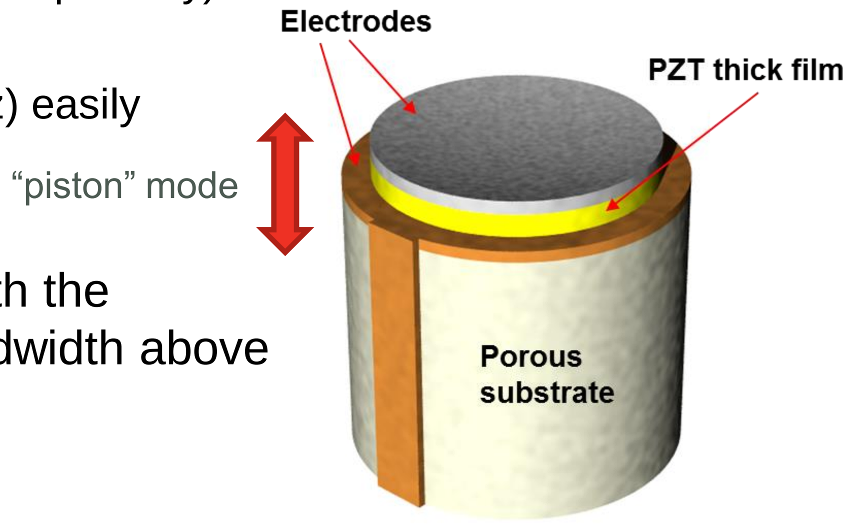
3 | Medical imaging

4 | Impact detection

5 | Motion sensor

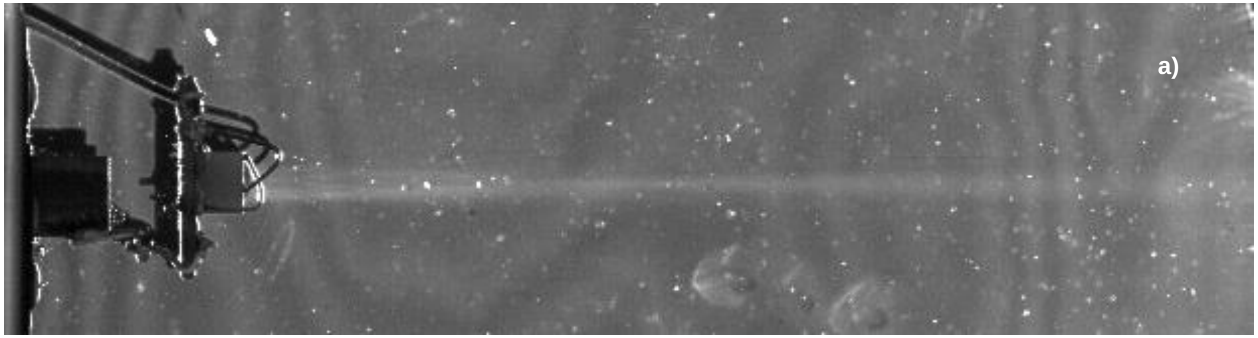
High-frequency ultrasonic transducers

- The characteristics of the printed thick film make it a perfect candidate for medical imaging due to the following:
  - Low acoustic impedance (because of porosity)
  - Low permittivity
  - High frequency (more than 20 MHz) easily obtained without machining
- When the thick film is combined with the optimised substrate, a relative bandwidth above 100 % is measured



Typical structure of a thick film based HF acoustic transducer

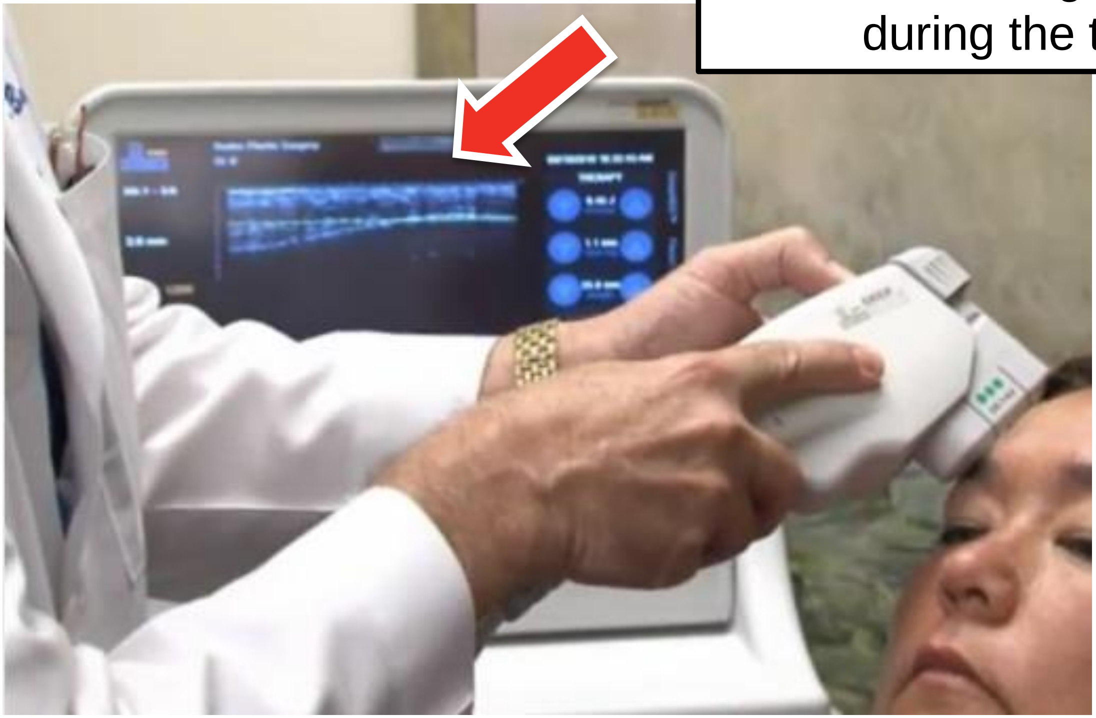
High-frequency ultrasonic transducers – acoustic field



Acoustic field of thick film transducers measured by means of Schlieren setup,
a) flat transducer, b) focused transducer (courtesy of A. Nowicki, IPPT).

High-frequency ultrasonic transducers – medical imaging

Real-time image of soft tissue during the treatment



Source: Ulthera video http://www.youtube.com/watch?v=XhafnO0uB_k

Application examples

1 | Structural health monitoring

2 | Energy harvesting

3 | Medical imaging

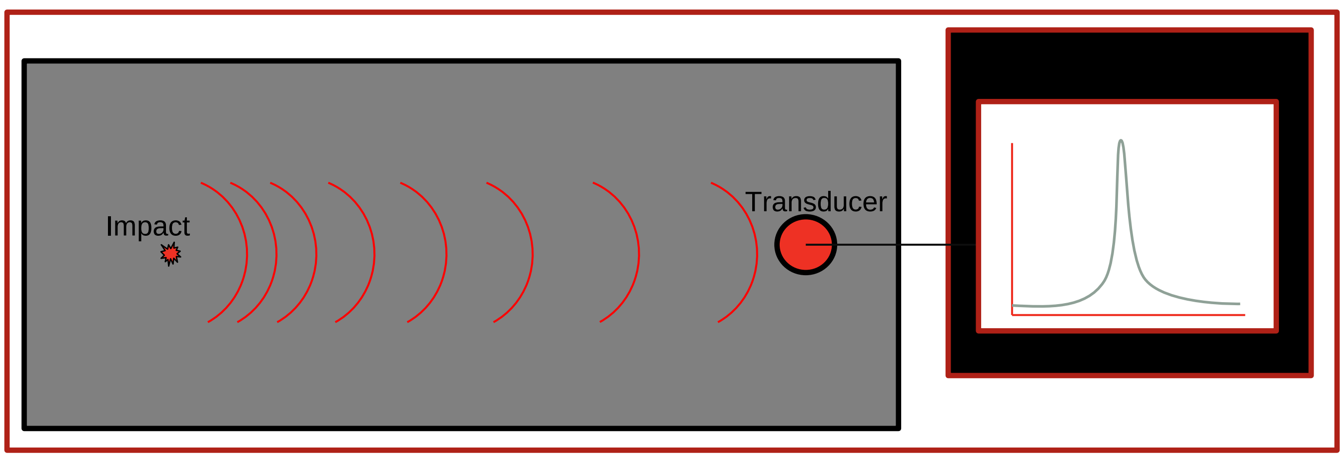
4 | **Impact detection**

5 | Motion sensor

Ultrasonic impact detection

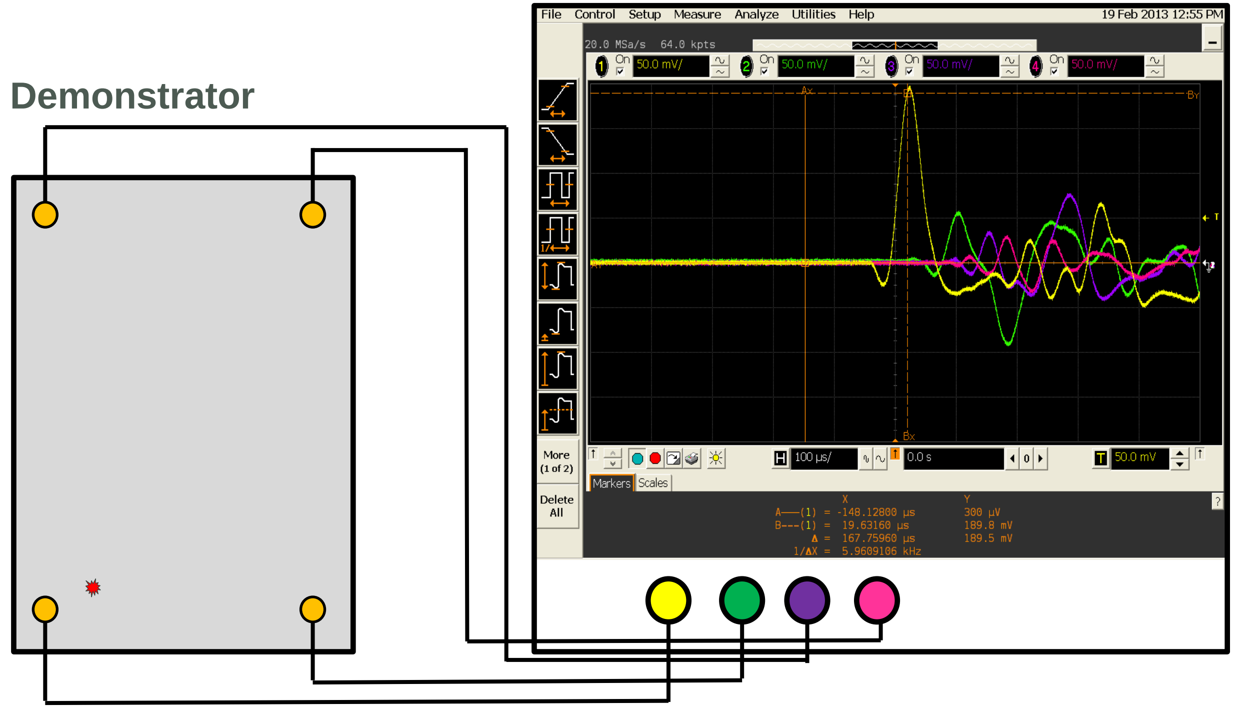
» What is it?
  - Passive SHM method based on measuring the acoustic emission from an impact.

» How is it done?
  - Piezoelectric transducers convert the acoustic wave into an electric output.



Test setup and procedure

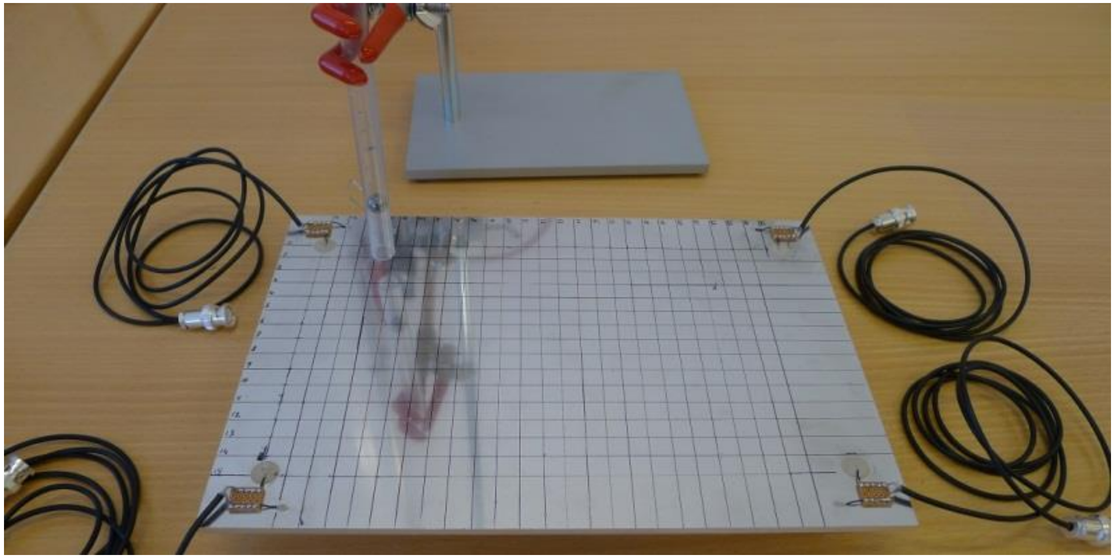
- The sensors were connected to four ports of an oscilloscope
- No extra signal conditioning was used



Test setup and procedure II

- To track impacts a grid was drawn on the aluminium plate
- A tube was fixed and used to control drop distance of a steel ball

- 153 impacts recorded
- Drop heights ranged from 2 cm to15 cm

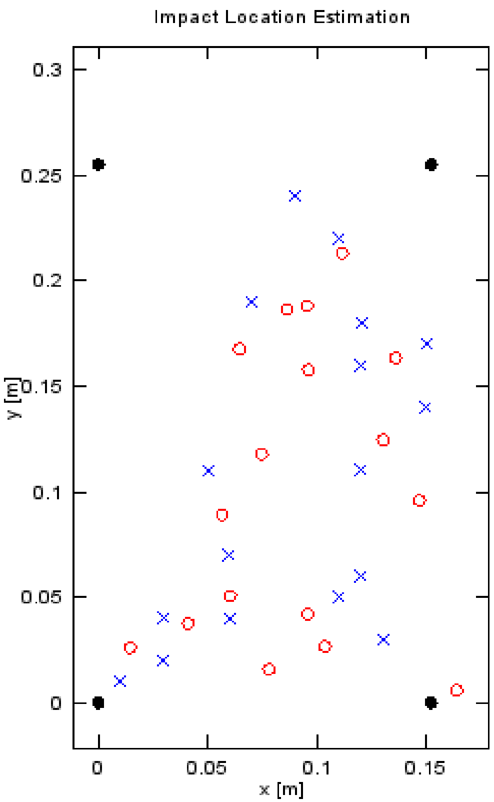


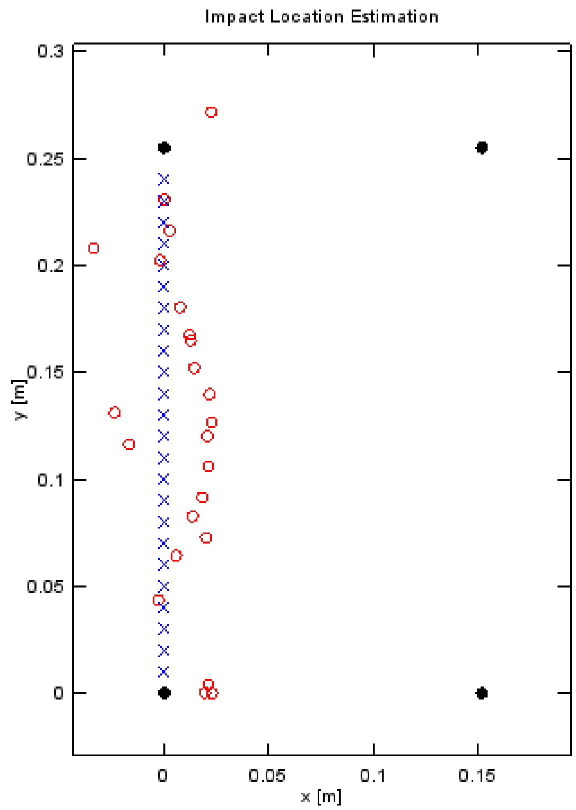
Impact localization

» Sample size: 153

» 90.2 % had an error < 5 cm

x Actual impact location
o Estimated impact location





Application examples

1 | Structural health monitoring

2 | Energy harvesting

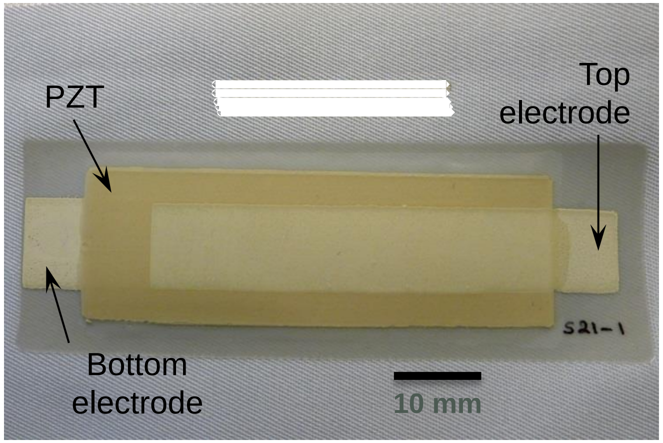
3 | Medical imaging

4 | Impact detection

5 | **Motion sensor**

Piezoelectric motion/displacement sensor

- Operates in 31 mode, the active film being sandwiched between electrodes
- The entire structure can be encapsulated with PVC or UV-curable dielectrics
- Flexible and applicable on a variety of substrates, e.g. fabrics and polymers



PiezoPaint™ motion sensor on polyester cotton fabric

[MICROFLEX, FP7]

Piezoelectric motion/displacement sensor

- VIDEO

Conclusions

- Properties of PZT thick films are inherently different to the properties of the bulk materials, and may depend on the substrate (clamping effect, chemical reactions)
- Porosity in the thick films may be very beneficial in certain applications!
- The InSensor™ PZT material system is compatible with a number of different substrates: Silicon, stainless steel, alumina, LTCC
- A number of different applications can be covered using PZT thick films due to their very good piezoelectric properties, including:
  - Medium- and high-frequency acoustic transducers
  - Energy harvesting devices
  - Integrated sensors
- Since the PZT thick film technology is application driven it offers complementary solutions filling the gap between thin films and bulk ceramic (especially the area of integrated devices)
- PiezoPaint™ printable piezoelectric material enables design and manufacturing of sensors, actuators and transducers on a variety of flexible substrates, including textiles and polymers

Acknowledgements

» AISHA II, Aircraft Integrated Structural Health Assessment II (CP, AAT-2007-212912)
» MICROFLEX, Micro fabrication production technology for MEMS on new emerging smart textiles/flexibles (CP, NMP-IP-2008-211335-2)
» Danish National Advanced Technology Foundation, contract no. 036-2009-1

» Prof. Erik V. Thomsen, Anders Lei, DTU Nanotech, Denmark
» Prof. Christ Glorieux, Sebastiaan Creten, ATF KU Leuven, Belgium
» Prof. Andrzej Nowicki, IPPT, Warsaw, Poland

Thank you

Conclusions (EH)

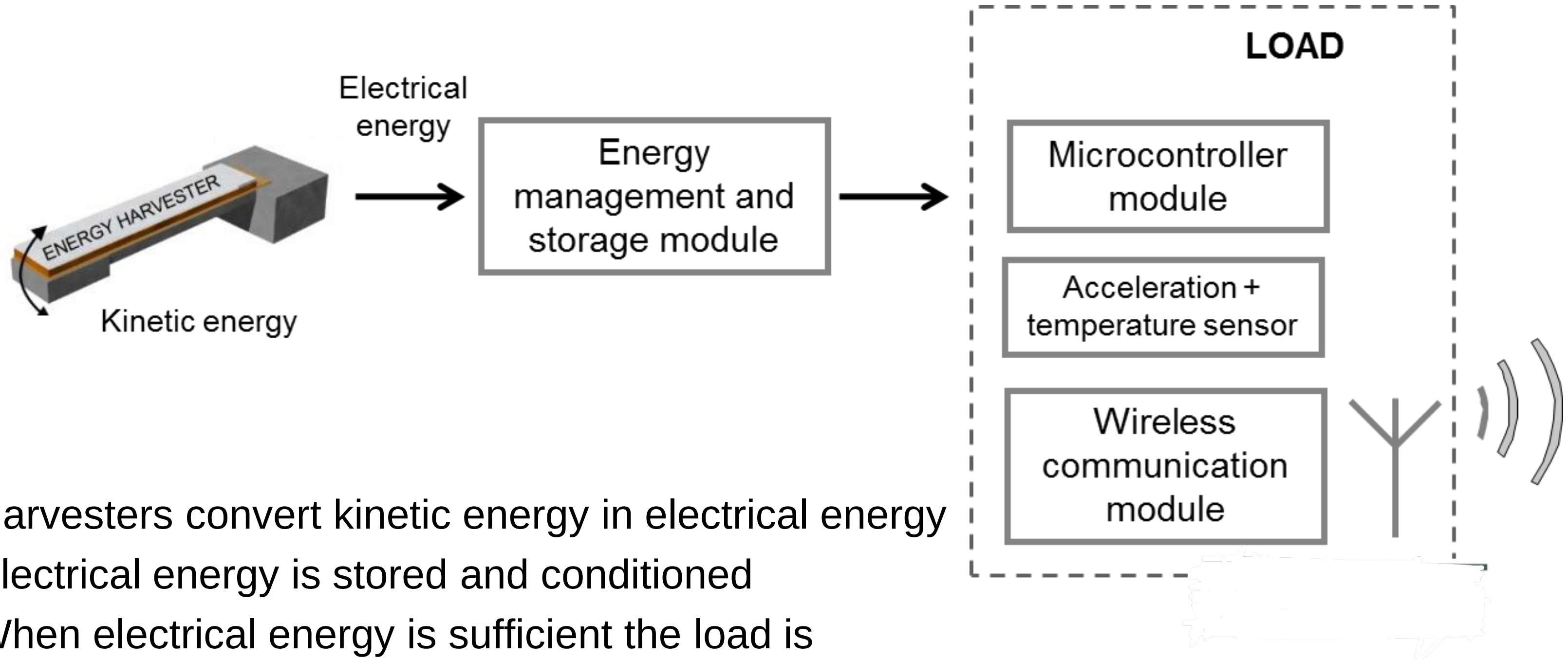
- The EH devices are capable of generation of 15 to 20 μW of power at moderate accelerations of about ~0.3 *g* RMS
- The PZT thick film micro generators can successfully power sensor nodes, enabling energy autonomous, wireless measurement of acceleration, temperature and humidity at low levels of vibration e.g. 0.25 *g* RMS
- The data is easily accessible through number of standard network interfaces: LAN, Wi-Fi, 3G
- The wireless and battery-less sensor systems have been successfully applied in monitoring of industrial equipment
- The presented network of sensors can be applied in permanent as well as temporary monitoring in e.g. difficult to access locations
- Energy harvesting based sensor nodes enable systems that are:
  - Energy autonomous
  - Maintenance-free
  - Very easy to deploy

General features of the EH system

- Micro generator level
  - Highly integrated
  - Small (millimeter scale)
  - Sourcing energy from vibrations

- System level
  - Low weight
  - Energy autonomous
  - Wireless
  - Long life
  - Wide range of working temperatures

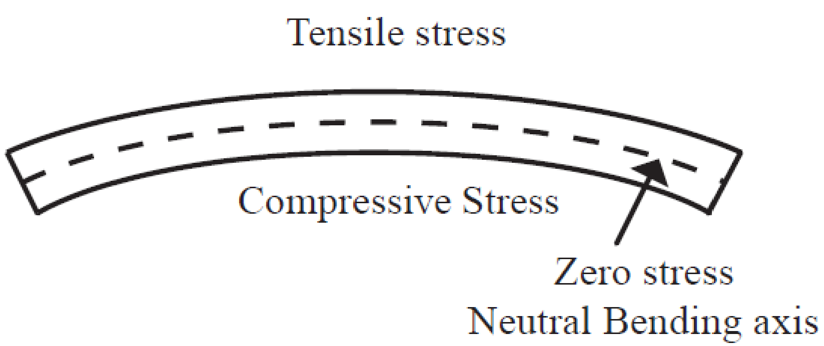
Sensor node architecture



- Harvesters convert kinetic energy in electrical energy
- Electrical energy is stored and conditioned
- When electrical energy is sufficient the load is powered
- Microcontroller repeats acceleration measurement and data transmission at fixed time intervals

Design criteria for bending structures in energy harvesting

- Optimal design of a bending structure should assure the neutral bending axis to be located a the interface between active (PZT) and passive (Si) materials
- Typical device layer of an SoI wafer (20 µm) requires 30-40 µm of the active material (PZT)



$$\frac{t_{pzt}}{t_{Si}} = \sqrt{\frac{Y_{Si}}{Y_{PZT}}}$$

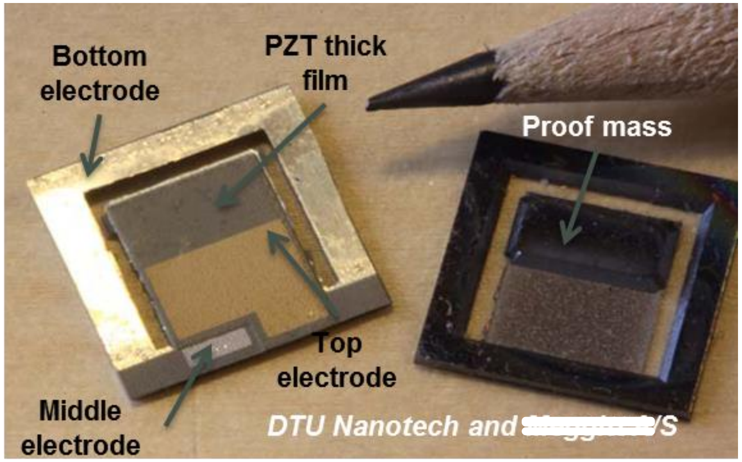
Y: Young's modulus

$$t_{pzt} = t_{Si} \cdot \sqrt{\frac{Y_{Si}}{Y_{PZT}}} = 20\ \mu\text{m} \cdot \sqrt{\frac{130\ \text{GPa}}{43.6\ \text{GPa}}} = 34.53\ \mu\text{m}$$

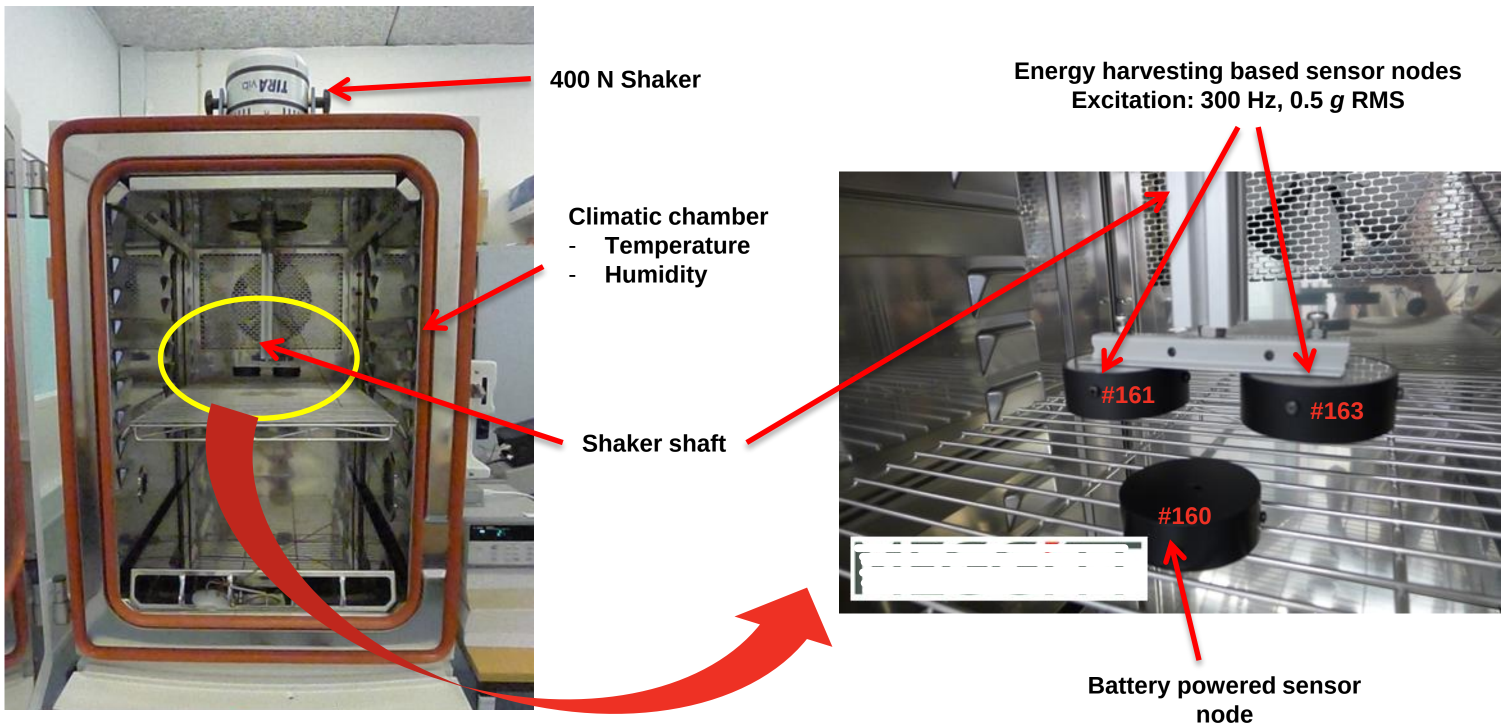
J.K. Olsen: Piezoelectric Components in Microfluidic Devices, Master Thesis, DTU, 2007

Energy Harvesting micro-generators – thick film based bimorph

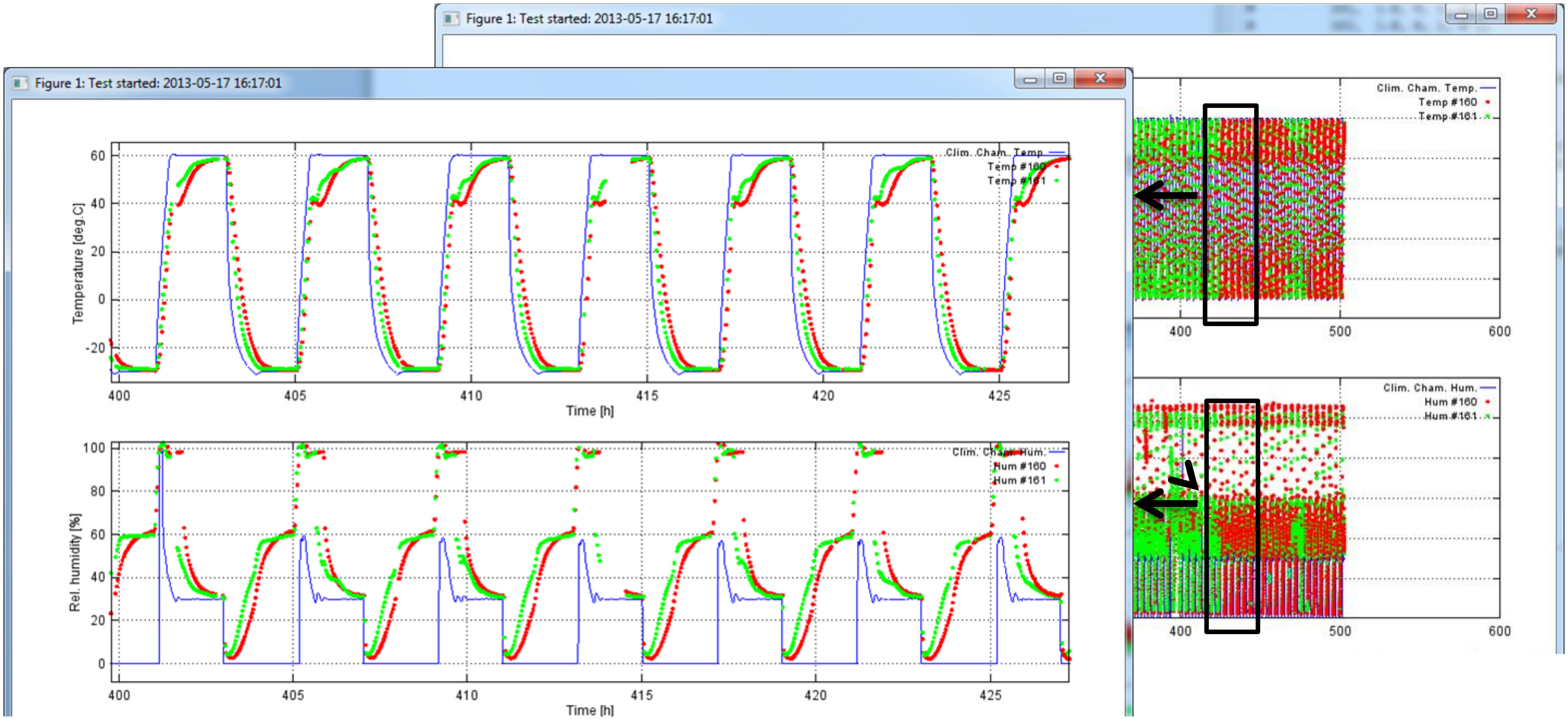
- Realized with silicon micromachining technology and PZT thick films deposited by screen-printing technique
- Single clamped cantilevers with a silicon proof mass at the free end
- Bimorph configuration
- 10 mm x10 mm lateral dimensions
- Higher voltage and power compared to unimorph
- Si/PZT fabrication + middle electrode + 2nd PZT layer + Si membrane removal



Climatic testing



500 hours test



TDoA demonstrator design