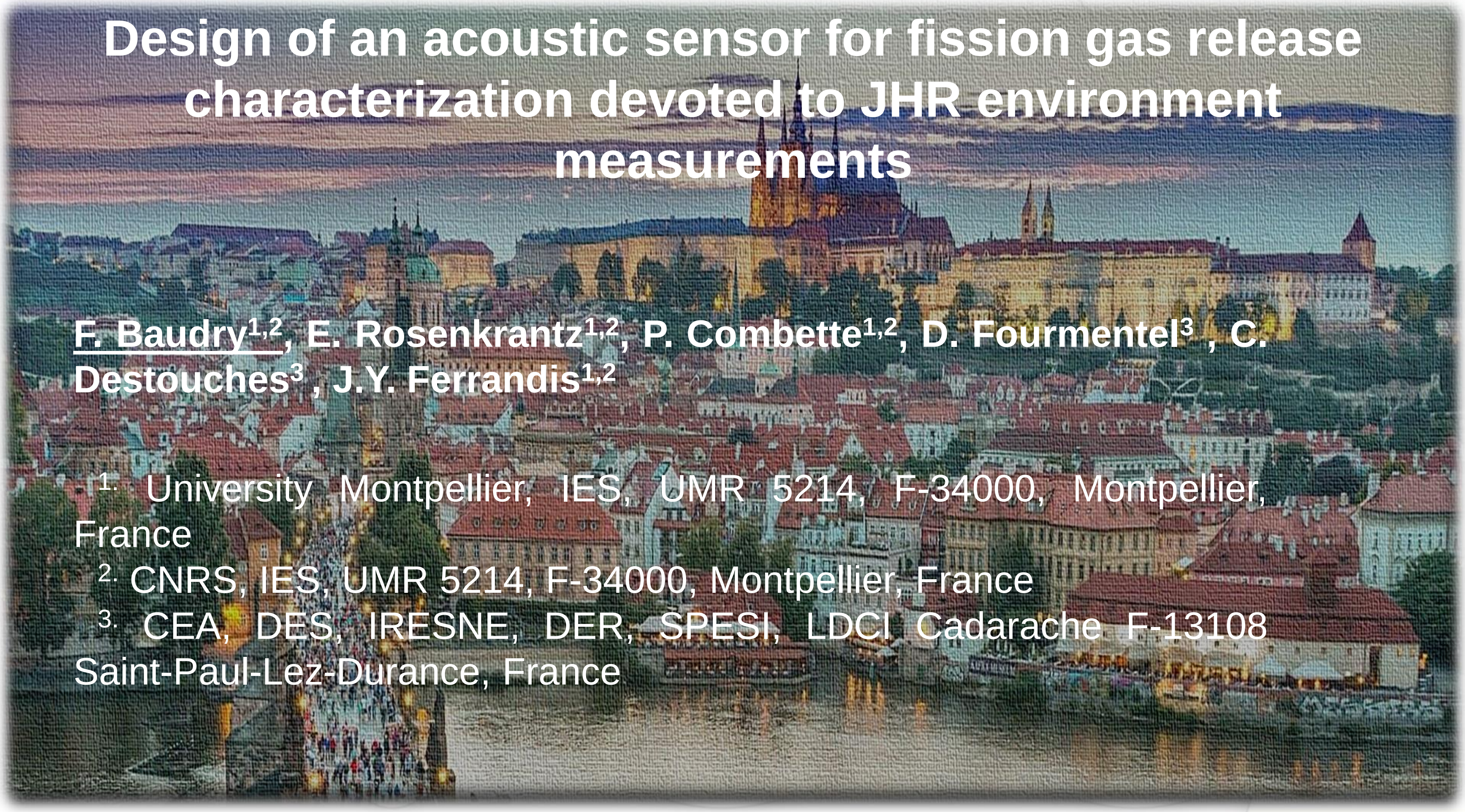

Design of an acoustic sensor for fission gas release characterization devoted to JHR environment measurements

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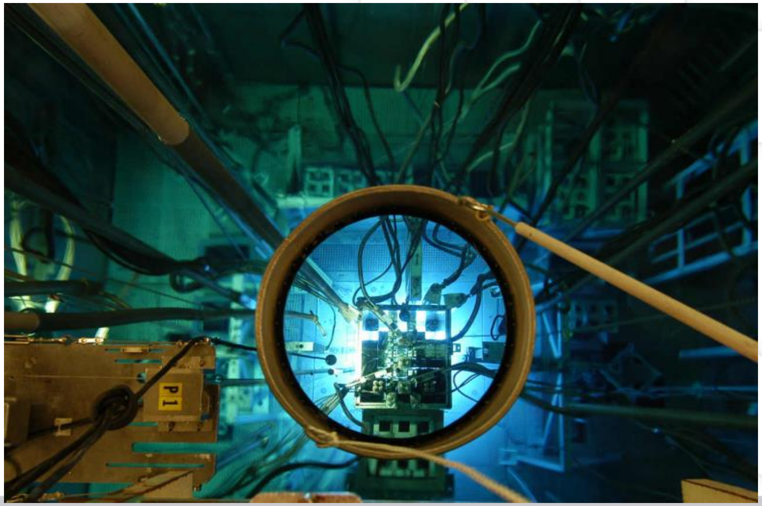
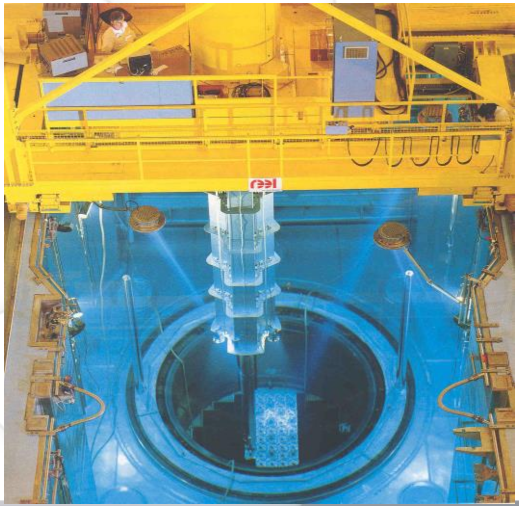
- **Presentation of the group of partners and the project**
- Chronology of the work on the gas composition devices
- Operating principle of the device
- Device design
- Device characterization

IES Acoustic team has R&D skills to develop innovative instrumentation in nuclear domain

- ○ **Measurement of the PCI (Pellet Cladding Interface) by acoustic imaging**
- ○ **Mechanical characterization of irradiated fuel**
- ○ **Estimation of the pressure and composition of a gas confined in PWR tube**
- ○ **Measurement of fission gas composition in experimental reactors**





Context : developement and fabrication of a new expérimental reactor Jules Horowitz (RJH)

- An experimental reactor is a nuclear installation in which we produce and maintain a chain reaction in order to obtain a flow of neutrons to be used during experimentation.
- Some are used to study and qualify the behaviour under irradiation of structural materials and fuel.
- Generally speaking, an experimental reactor requires instrumentation (temperature, inner pressure, chemical properties, structural evolution…)

Artist views of the new JHR

the aim of the partnership between CEA and IES (Institute of electronic and systems) is to develop a means of measuring the gas composition in a fuel rod for an experimental reactor

- Presentation of the group of partners and the project
- **Chronology of the work on the gas composition devices**
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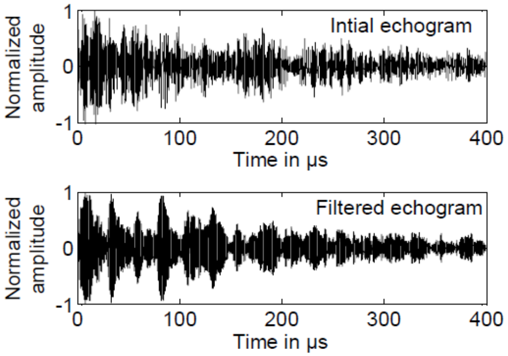
- Device design
- Device characterization

Timeline of the project

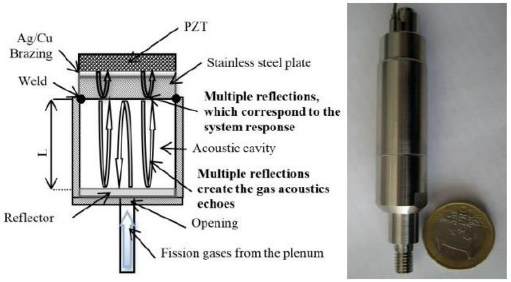
2000-2010 : Proof of concepts of a gas composition monitoring device in fuel rod [1]

NDT sensor for measurement of gaz composition [5]

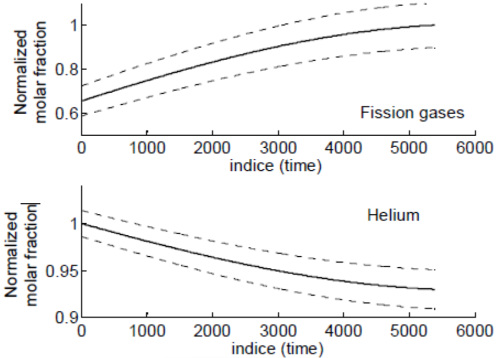


Raw signal in 90 Bar of helium and filtred signal by FFT[2]

2010 : Testing the gas composition sensor (CACP-1 REMORA 3) in OSIRIS [2]

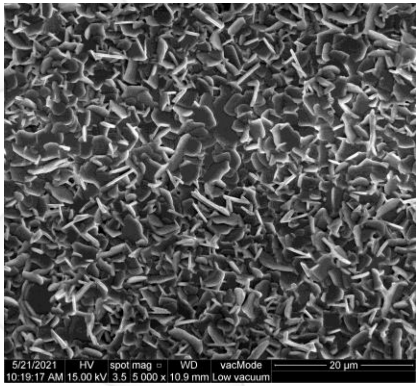


Acoustic sensor overview of CACP-1 2010 tested in OSIRIS [1]

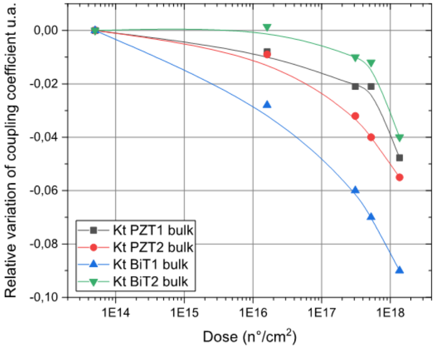


Variation of gas composition during maximal irradiation phase [2]

2011-20XX : Study of a new gas composition sensor with high temperature (< 300° C)



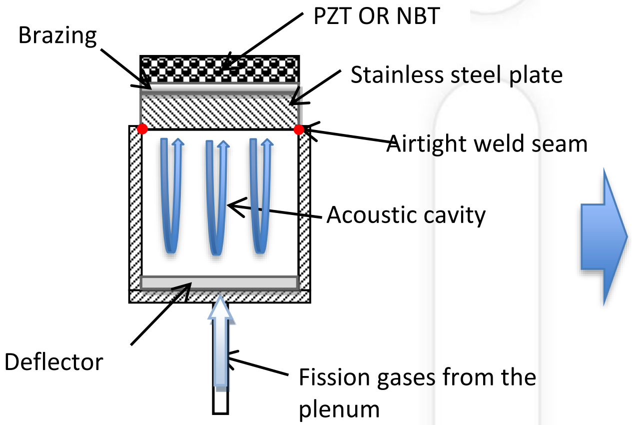
SEM picture × 5000 of high Curie temperature piezoelectric material PHD of F.Very and O.Gatsa



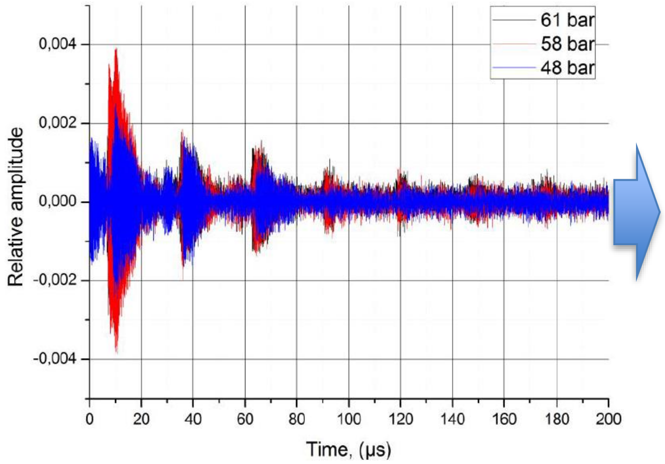
Irradiation study of piezoelectric elements at high Curie temperature (Animma 2019) [3]

- Presentation of the group of partners and the project
- Chronology of the work on the gas composition devices
- **Operating principle of the device**
- Device design
- Device characterization

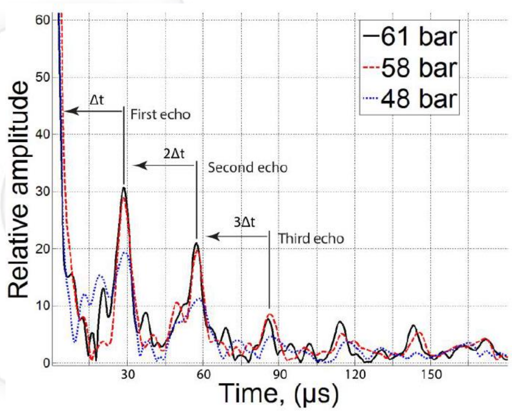
Acoustic sensor for gas composition measurement (REMORA3 generation)



schematic sectional view of the CACP 1 device



Echogram in Helium under pressure



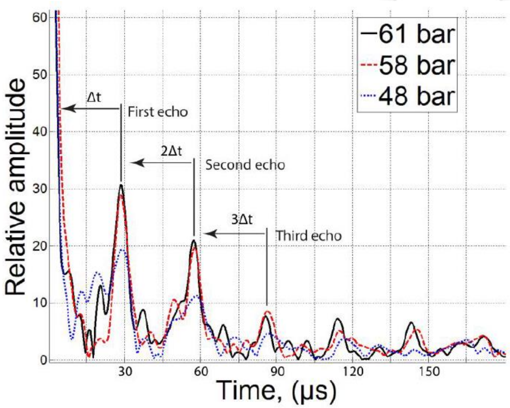
Filtered signal by FFT and RFFT

Then how pass from Δt to a gas composition measurement ?

Dependency of acoustic celerity and the molar mass of the gaz

$$c = \sqrt{\frac{\gamma RT}{M}}$$

With $c = \frac{2d}{\Delta t}$



Standard Acoustic measurements from gas cavity

equation of statistical physics linking the velocity of acoustic waves to a gas composition

Perfect gas = use the first order Viriel equation

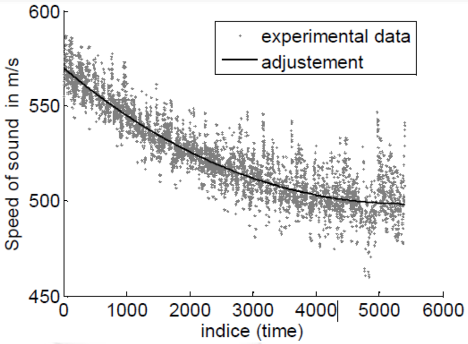
$$\sqrt{\frac{\gamma RT}{xM_{Xe/Kr}+(1-x)M_{He}}}$$

real gas = use either the Viriel or Redlich-Wong equation

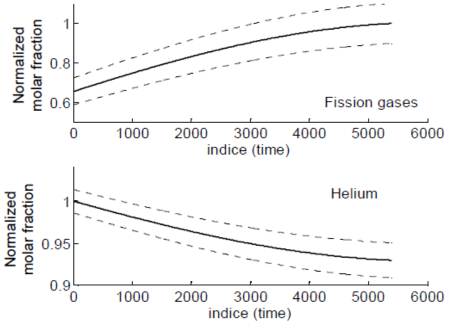
$$c^2 = \frac{\gamma RT}{M}\left[1+\left(2b-\frac{a}{RT^{3/2}}\right)D+3b^2D^2\right]$$

- The ratio $\frac{x_{Xe}}{x_{kr}}$ is known (12 for UO_2 and 17 for MOX)
- We have to know the initial gaz mixture (100% He for instance for t=0)

equation of statistical physics linking the velocity of acoustic waves to a gas composition



Decrease of the Speed of sound for a real mixture

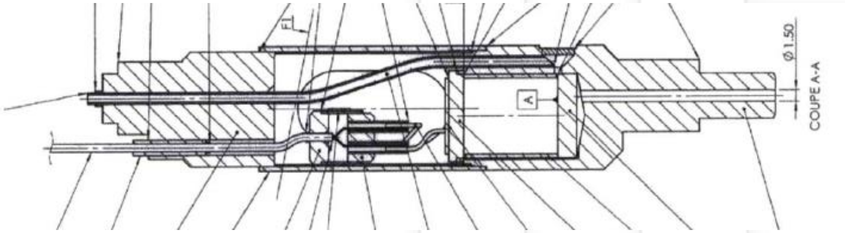


Estimation by equations of the ratio x between He and Xe/Kr

why up to date the gas composition monitoring device ?

Because the **GEN1- REMORA3 sensor** presents some limitations :

- **Mechanical coupling imperfection between the active element and substrate**
- **Parallelism issue due to fabrication technique**



- **Temperature limitation of an active element (PZT) at 200 °C → The NBT have an higher temperature limitations**

Two thesis (2015 - F. VERY & 2018 - O. GATSA) allowed us **to propose two solutions** :

- Direct screen printing of an active element onto alumina substrate to reduce the imperfection and non-parallelism influence
- Active element with a working temperature about 400 °C
- Both of these solutions have been validated under nuclear radiations [3]

My work consists to design, manufacture the new Acoustic instrumentation and GEN2- sensor

Now we have to study the structure of the device…

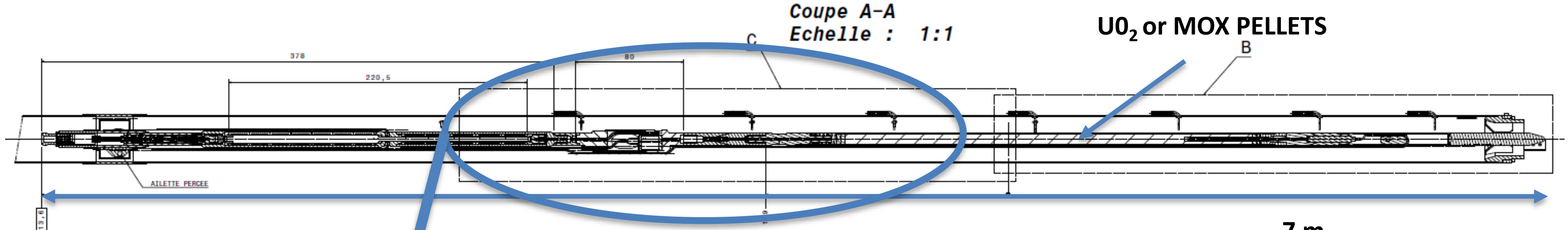
- Presentation of the group of partners and the project
- Chronology of the work on the gas composition devices
- Operating principle of the device
- **Device design**
- Device characterization

Device specifications

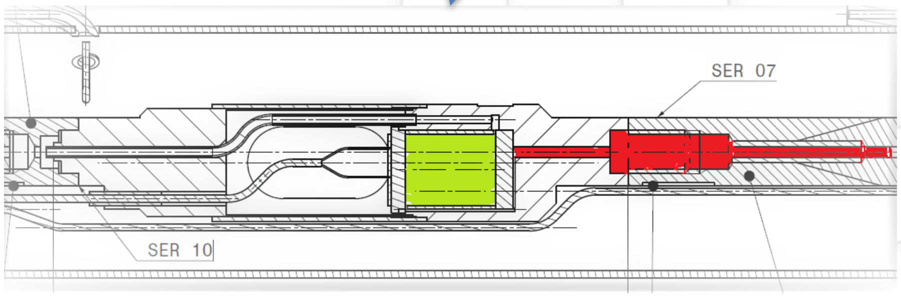
- Resist to a temperature of at least 350 ° C for Gen2-sensor → **Use of ceramics and refractory cement for the manufacturing of the devices**

- Radiation constraints → **Experiments have been done so as to test the NBT under harsh environment (Neutron flux, temperature…) (ANIMMA 2019)**

- Dimensional constraints → **must be able to fit in a cylinder of 15 mm diameter**



Global Cut view of the new instrumented fuel rod for JHR



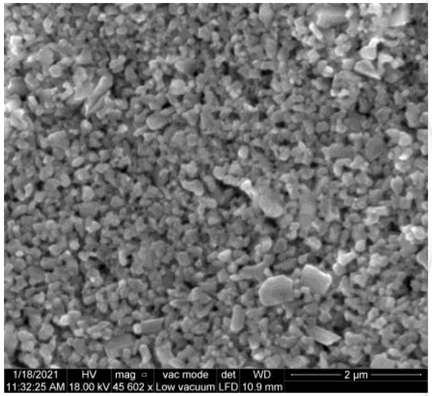
Cut view C

🟢 ***Cavity filled by HP gas***

🔴 ***Canalisation between fuel pellets and cavity***

Our sensor have to be integrated in this cavity…

Fabrication of the piezoelectric part

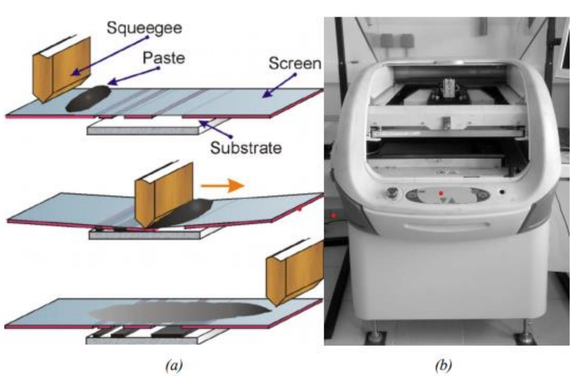


Powder of NBT

1

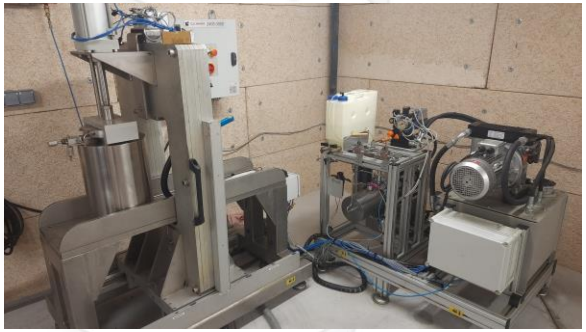
Mixed powder + binding agent

2



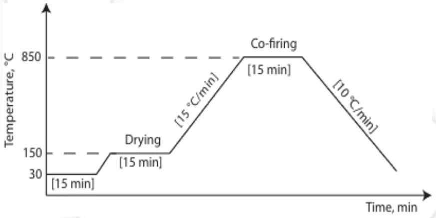
Screen printing deposition

3



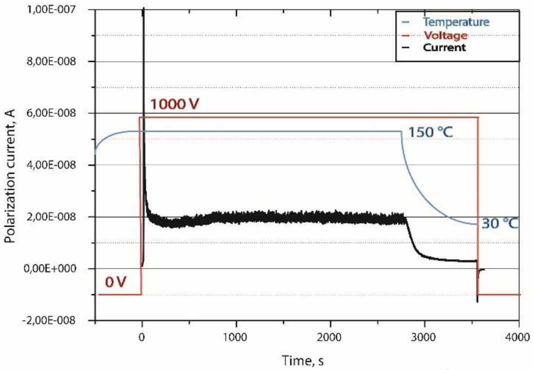
isostatic pressing

4



Firing

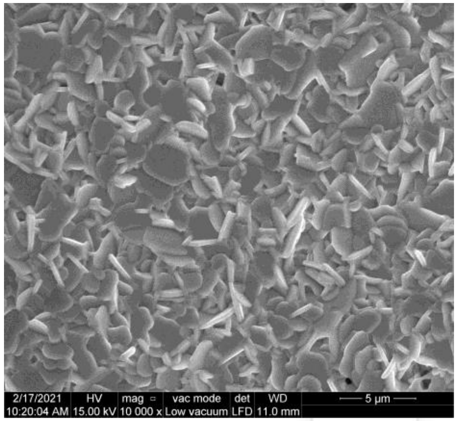
5



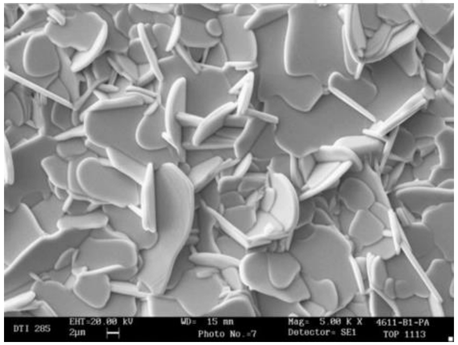
Polling step

Piezoelectric parts

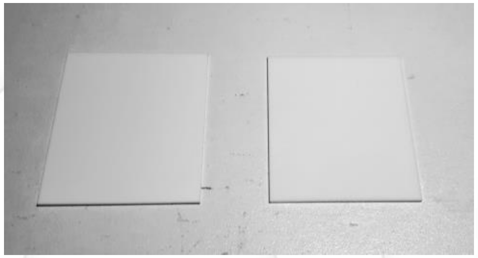
- Use of NBT (Sodium Bismuth Titanate) similar to PZ46 marketed by MEGGIT® (no longer commercialize) → **Has a high Curie temperature and a sufficient S/N ratio for our applications (at least 350° C)**



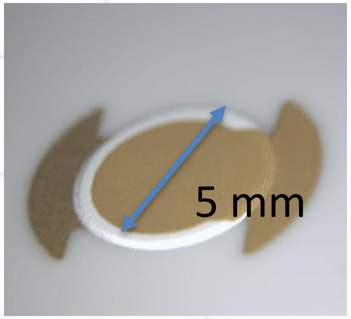
SEM pictures of our NBT



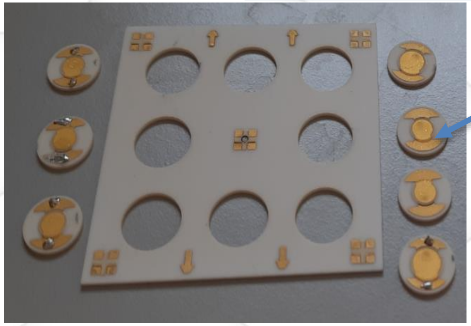
SEM pictures of marketed PZ46® from MEGGIT®



screen printing on MACOR and Alumina (Al_2O_3)



use of Pt and Au electrodes that can reach temperatures of at least 1000° C



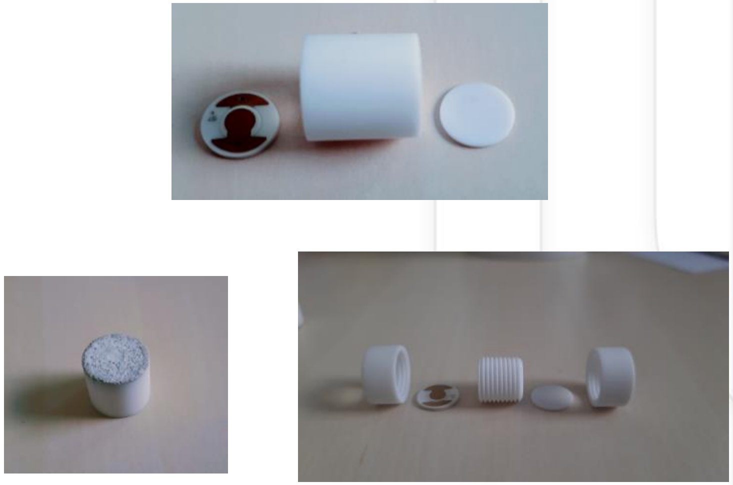
Ceramic disk with piezoelectrics parts

Fabrication of matrix plates 8 piezoelectrics elements by screen printing

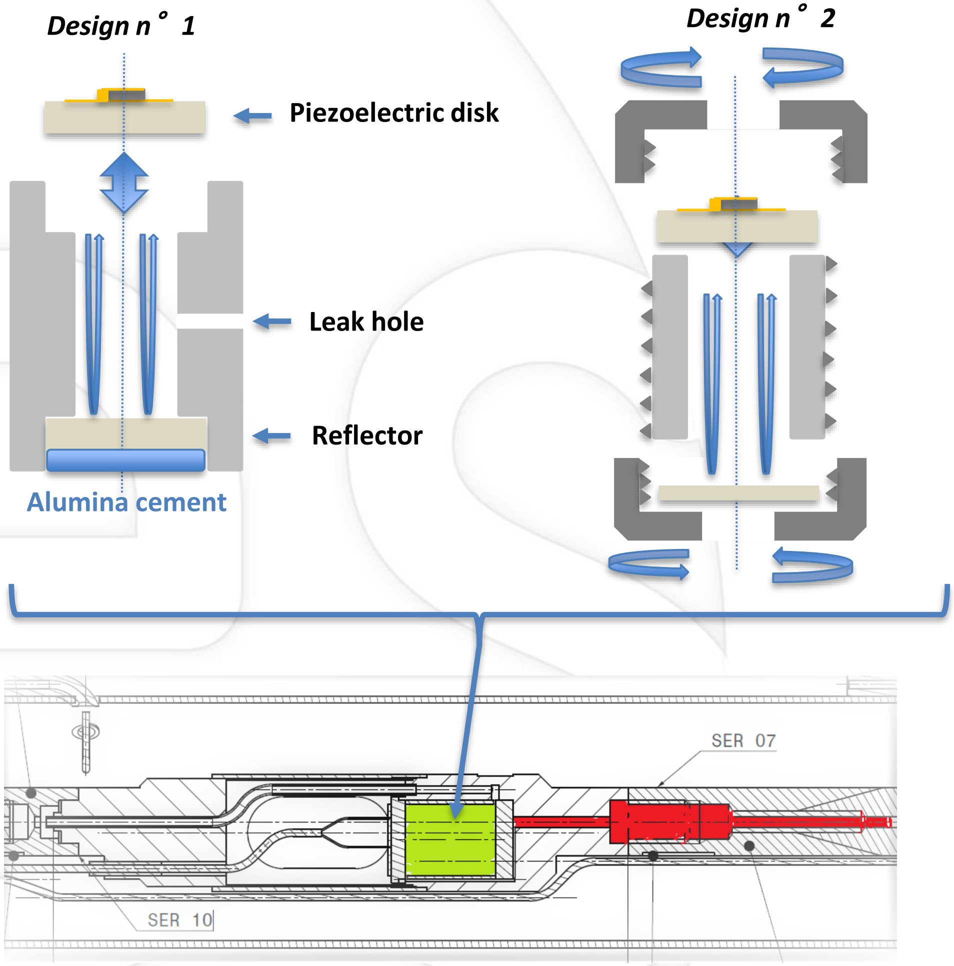
Sensor body

The sensor Body is made of vitroceramic MACOR for two reasons :

- **Low dismatch of TCE between elements of the sensor (α_{Al2O3}= 8,6×10^{-6} K^{-1} VS α_{NBT} = 7×10^{-6} K^{-1} VS α_{MACOR} = 9×10^{-6} K^{-1})**
- **Each parts can be bounded by alumina cement (resilient until T_{max}=1400° C)**



Designs 1 & 2 of acoustics devices



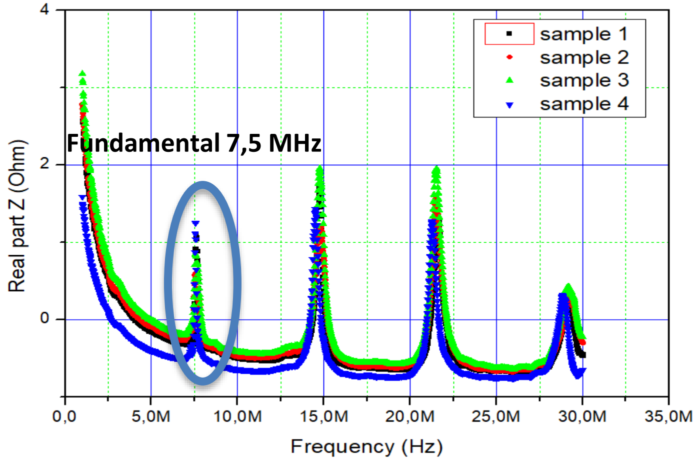
Integration of the sensor directly in the pressurized cavity

- Presentation of the group of partners and the project
- Chronology of the work on the gas composition devices
- Operating principle of the device
- Device design
- **Device characterization and results**

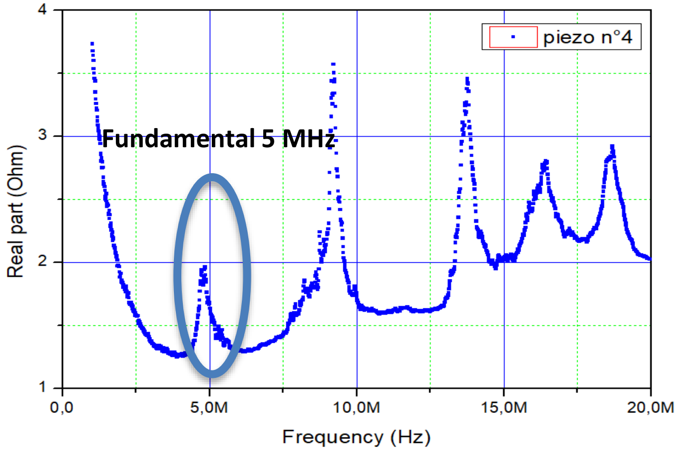
Impedance characterization

First of all, for characterization in a viscoelastic medium like gas, the resonance must be around 5 MHz :

- With a numeric model (KLM), we have estimated optimals dimensions and thickness for the sensor
- For a 700 µm thickness alumina substrate and 90 µm NBT element the fundamental should be around 5 MHz



Example of NBT sample impedance for 50 µm thickness



Example of NBT sample impedance for 90 µm thickness

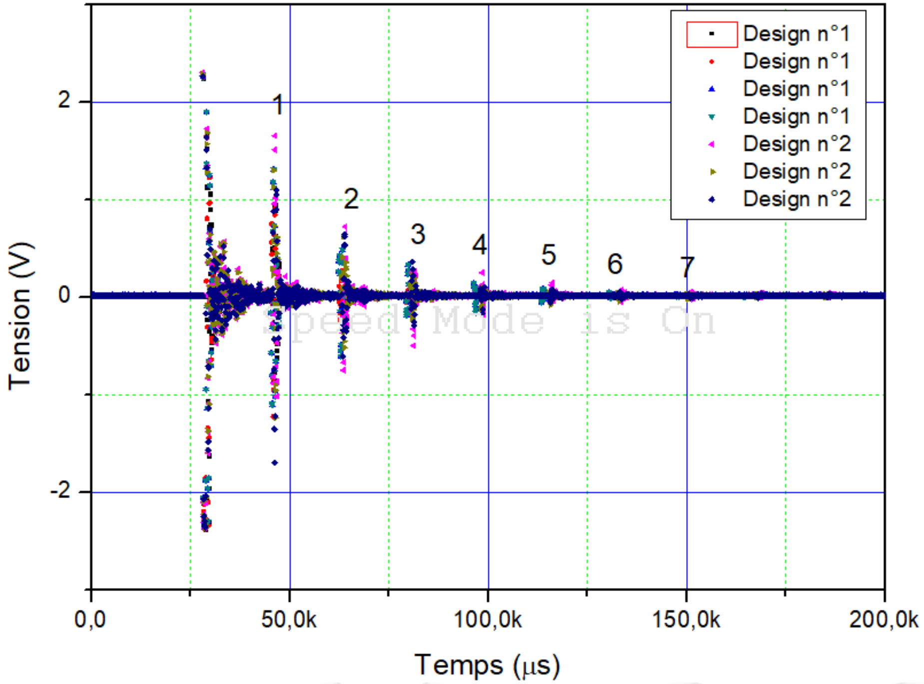
NBT devices with Au electrodes and Bounded Au wires

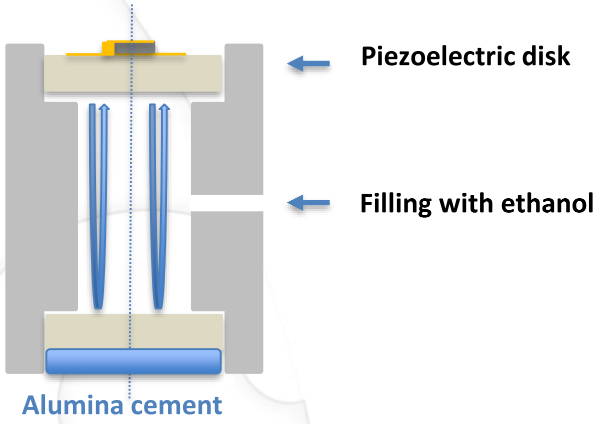
Keysight 4990A

Tests with ethanol as acoustic medium

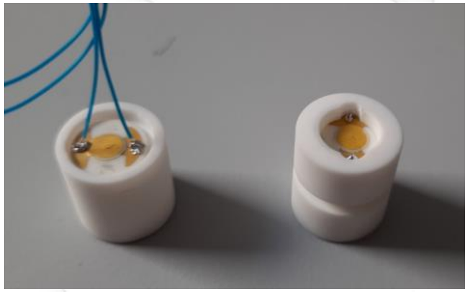
The preliminary tests consist in filling the device with ethanol in order to use it as propagation medium :

- **Decrease of echoes → Good parallelism**
- **Good S/N ratio for liquid medium**





Filling the resonant cavity with ethanol



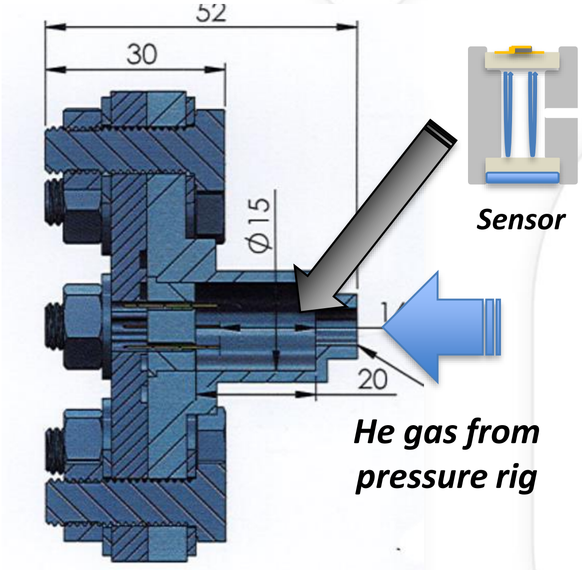
Design n° 1 and n° 2

7 acoustic reflexions in ethanol medium and the next measurements in pressurized He

Pressure test bench

The acoustic team of *IES* and *TMI Orion* have developpped a specific pressurized test bench for our laboratory :

- Possibility to be use up to 200 Bar for T=200 °C
- 4 sealed contacts permitted to connect 1 thermocouple and 1 acoustic sensor



Pressure chamber made of INOX 316L

pressure rig with reserve of Helium

The first experiment under gas pressure are planned for this summer

Conclusions

- NBT seems to be a suitable material for the realization of this new device
- the new sensor will have a 100% ceramic composition
- Preliminary tests with ethanol have been successful and are promising for the future of the project

Bibliographie

[1] D. Fourmentel, J. F. Villard, J. Y. Ferrandis, F. Augereau, E. Rosenkrantz, and M. Dierckx « Acoustic Sensor for In-Pile Fuel Rod Fission Gas Release Measurement »
[2] E. Rosenkrantz, J.Y. Ferrandis, F. Augereau, T. Lambert, D. Fourmentel, X. Tiratay, An innovative acoustic sensor for first in-pile “ fission gas release determination - REMORA3 experiment »
[3] JY. FERRANDIS1, O. GATSA1, P. COMBETTE1, D. FOURMENTEL2, C. DESTOUCHES2, V. RADULOVIC3, L. SNOJ, « Acoustic instrumentation of the new generation of MTR: effect of nuclear radiation on modified Bismuth Titanate piezoelectric elements “
[4] R. Torah, S. P. Beeby, et N. M. White, « An improved thick-film piezoelectric material by powder blending and enhanced processing parameters »
[5] J. Y. Ferrandis, E. Rosenkrantz, G. Lévêque, D. Baron, J. C. Segura, G. Cécilia, and O. Provitina, Full-Scale Hot Cell Test of an Acoustic SensorDedicated to Measurement of the InternalGas Pressure and Composition of aLWR Nuclear Fuel Rod, 2011