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R&D Studies for the Development of Acoustic Sensors Fordark Matter Bubble Chamber Detectors

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Abstract: PICO Dark Matter bubble chamber detectors use piezoelectric sensors in order to detect and discriminate the acoustic signals emitted by the bubbles grown within the superheated fluid from a nuclear recoil produced by a particle interaction. These sensors are attached on the outside walls of the vessel containing the superheated fluid. The acoustic discrimination depends strongly of the properties of the complete sensor and there are constrains as well in the size and radiopurity of the piezoelectric ceramics. With the aim of understanding the complete acoustic process and optimizing the sensor system, a test bench for the characterization of the sensors glued to the vessel has been developed. The sensor response for different piezoelectric materials, geometries, matching layers and experimental designs has been measured and contrasted with FEM simulations and analytical models. The results of these studies and designs lead us to have a design criterion for the construction of specific sensors for next generation of PICO detectors (250 L bubble chambers).

Keywords: Dark Matter; Bubble Chamber; Piezoelectric sensors; Acoustic transducers; Acoustic detection; Acoustics test bench.

1. Introduction

Understanding the nature of dark matter is one of the most important goals in modern particle physics. A leading candidate to explain the dark matter is a relic density of cold, non-baryonic Weakly Interacting Massive Particles (WIMPs), and direct detection dark matter experiments hope to observe the nuclei recoiling from the rare collisions of WIMPs with ordinary matter. The superheated detector technology has been at the forefront of Dark Matter searches, using refrigerant targets. The PICO Collaboration (formed from the merger of PICASSO and COUPP) uses a bubble chamber detector type consisting of a fused-silica jar filled with hydraulic fluid and tapped with a buffer layer. Several lead zirconate (PZT) piezoelectric acoustic transducers epoxied to the exterior of the fused-silica jar recorded the acoustic emission from bubble nucleations [1].

In previous detectors, high levels of radioactivity in the transducers provided a measurable neutron rate. For latest PICO-2L and PICO-60, PZT sensors from source material with a factor 100 reduction in radioactivity were developed in an ultra-high purity environment to prevent any contamination during mixing, calcination, and sintering. An acoustic parameter (AP) is used to characterize the acoustic power of an event that is useful to discriminate between different kinds of interacting particles. The acoustic signal is analyzed in frequency bands, and each band is corrected for the position of the bubble within the chamber.

In this work we show the R&D studies made in the Acoustic Test Bench of Gandia [2] in order to study the characterization of piezoelectric materials, the acoustic calibration and optimization of acoustic sensors and the simulation of its acusto-electro-mechanical behavior to thereby continue collaborating in the development of sensors for future versions of PICO detectors, for instance the 250 L PICO bubble chamber detector.

2. Obtaining Piezoelectric Coefficients

The determination of complete piezoelectric coefficients is performed based on the EN 50324-02 standard [3] in which ceramics with different polarizations and geometries have to be used.

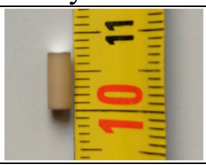
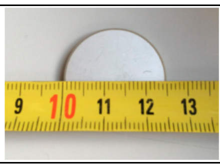
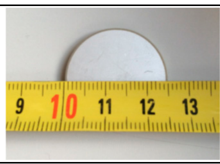
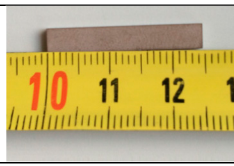
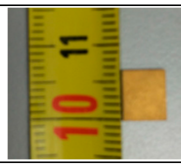
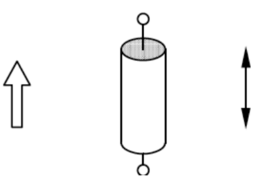
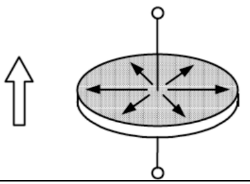
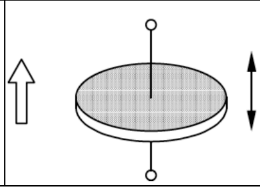
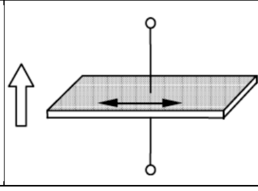
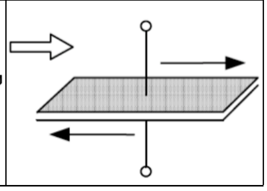
Longitudinal (33)	Thickness (t)	Radial (p)	Transversal (31)	Shear (15)
Cylinder	Disc	Disc	Plate	Plate
				
Ø=3 mm, L=8 mm	Ø=25 mm, T=2 mm	Ø=25 mm, T=2 mm	L=25 mm, T=2 mm	L=7 mm, T=1 mm
				

Figure 1. PIC255 ceramics used for obtaining piezoelectric coefficients following DIN EN 50324-02 standard. ⇨ indicates polarization direction. ⟶ indicates displacement direction in each mode.

According to this standard, five geometries of the same piezoelectric material PIC255 polarized properly (that characterize five distinct modes of vibration) are used to measure the resonance frequencies (f_r) and antiresonance (f_a) with an impedance analyser, when they vibrate freely. From each of them, the corresponding electromechanical coupling factors (k) are obtained. Additionally, knowing the resonance and antiresonance frequencies and with the measurements of the geometry (width, length, thickness, radius) and material density, each of the coefficients of the piezoelectric matrices can be obtained. Such relationships can be obtained following the standard mentioned. Figure 1 shows the ceramics used and their properties. From each of these samples, real and imaginary parts of the electrical impedance have been obtained with a Wayner Kerr Electronics 6500P impedance analyser.

3. Simulations of Piezoelectric Sensors

The FEM simulation of piezoelectric ceramics have been carried out in COMSOL Multiphysics. The input parameters are the coefficients of the elasticity matrix c^E, the coupling matrix e, the permittivity matrix ε^S, the density ρ, and both the mechanical and dielectric losses. Furthermore, in the geometrical model, the surface of the electrodes and the feeding electrical potential V should be set.

Among the wide range of possible outputs that can be calculated, none is exactly the electrical impedance or admittance. However, we can still calculate it from the inward surface charge density J in the electrodes and the potential V. The figure 2 shows the comparison of the measurement results and the FEM simulation for one of the studied transducers (25 mm diameter and 2 mm thickness PIC 255 ceramic). In the experiment, the voltage used was 500 mV_{pp}, and the frequency was swept from 100 Hz to 1 MHz with a sweep interval of 100 Hz. We can see that both results are in a quite good agreement. The local minima and maxima appearing in the impedance curve correspond to the resonance and antiresonance peaks, respectively, of the radial modes (low freq.) and thickness mode.

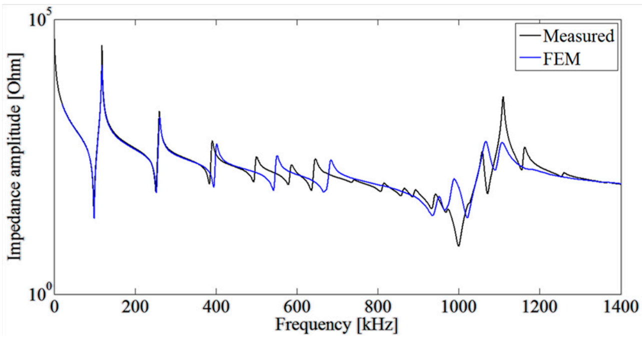


Figure 2. Impedance measurements and FEM simulations for the PIC 255 ceramic disc.

4. Calibration of piezoelectric sensors

The sensitivity of each transducer has been quantified by the so-called Received Voltage Response (RVR). From the set of PIC 255 ceramics studied, we have used the same four species of two different types: a disk of 2 mm thickness and 25 mm diameter, and a cylindrical ceramic of 5 mm thickness and 10 mm diameter. These ceramics have been selected since they are similar to the ones already used in the PICO-2L and PICO-60 detectors. They are reduced in size and have high sensitivity in the 50 - 150 kHz frequency range. Due to the spatial limitation of the measurement system and to the frequency range considered in the AP parameters, the sensitivity was calculated from 30 kHz to 250 kHz.

The ceramics were measured in two configurations that can be seen in figure 3. In configuration 1, the transducers are inside of a water tank, and in configuration 2 they are attached to a 13 cm-diameter vessel filled with water. All measures are controlled by the generation-reception PXI-1031 system acquisition and the signals are post-processed in Matlab. The experimental method and the signal processing techniques are similar to the ones presented in [4].

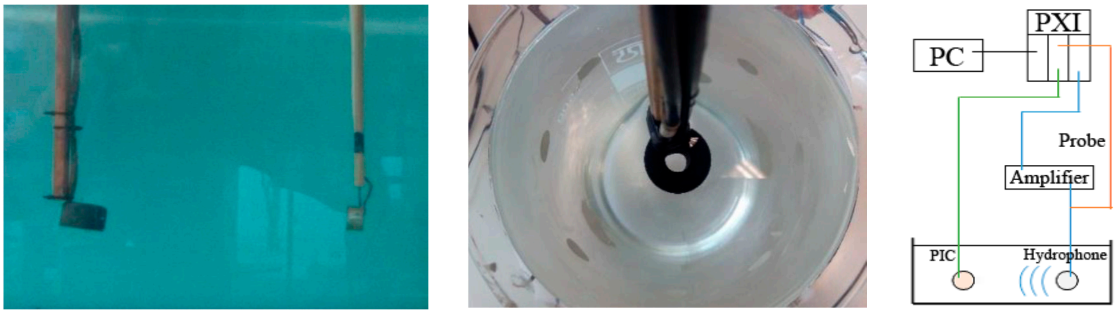


Figure 3. Left: configuration 1 with a FFR SX30 reference transducer). Center: configuration 2 with FFR SX60 reference hydrophone. Right: scheme of the experimental setup.

5. Optimization of the Acoustic Response

In PICO bubble detectors the target fluid (superheated liquid) is located within a vessel and the acoustic sensors are glued on the outer walls of the vessel detector. Then, we should optimize the sound transmission between the fluid and the ceramic, with the restriction that there is an intermediate medium (vessel wall) whose characteristics cannot be modified. With this aim, we have implemented a multilayer acoustic transmission model and made a series of experimental measurements to test it. The model consists of incorporating one or more layers between the receiving face of the piezoelectric element and the acoustic load. Imposing the conditions of pressure continuity and particle velocity continuity at each of the interfaces, we can obtain the total acoustic transmission coefficient [5].

In this study we are interested in the particular case of two layers: a first layer of 2.2 mm thick pyrex glass, which cannot be changed, and a second layer that can be designed choosing the material and dimensions. Knowing the characteristic acoustic impedance of the pyrex ($Z_i \sim 11.0 MRayls$) and of the piezo ($Z_t \sim 18.4 MRayls$), the ideal matching layer between them should have an impedance of $Z_1 = \sqrt{Z_i \cdot Z_t} = 14.2\ MRayls$. Aluminium was selected for the matching layer since the impedance ($Z_1 = 17.2\ MRayls$) is quite close to the best value. Additionally it is an affordable material and has low attenuation for acoustic waves.

6. Results

As explained in sections 2 and 3 the coupling factors k can be obtained experimentally and numerically, respectively, taking into account the values of the resonant and antiresonant frequencies. Table 1 shows the results contrasted with those from the manufacturer datasheet. The results are in good agreement except in the case of the measured cylinder (k_{33}).

Table 1. Comparison of the PIC 255 electromechanical coupling factors (k) from the measurements and from manufacturer datasheet.

	k_{33}	k_p	k_t	k_{31}	k_{15}
Manufacturer	0.691	0.620	0.471	0.351	0.661
Measured	0.242	0.624	0.471	0.351	0.628
Simulation	0.695	0.619	0.564	0.346	0.689

Figure 4 shows the sensitivity of each ceramic both free in the water tank (conf. 1) and glued to the vessel (conf. 2). Figure 5 shows the sensitivity difference between the ceramics attached to the vessel, with and without ML. There is a clear increase for some frequencies, except for C3 that might have a problem of sticking. The peaks have a larger frequency width for the case of discs than for the cylinder ceramics. Taking into account the frequency of the maximum sensitivity peaks in configuration 1 and 2 with different ML length, we can contrast the theoretical model for transmission of one and two layers, respectively. The results are shown in Figure 6.

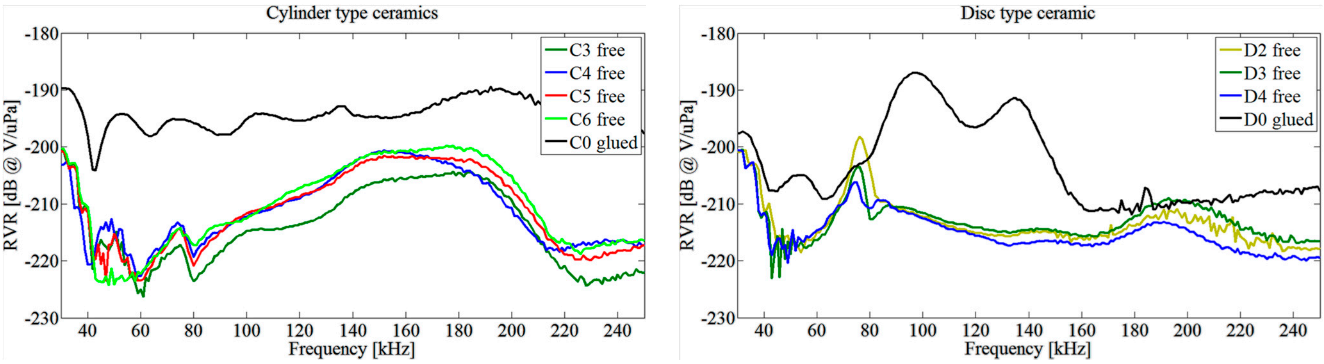


Figure 4. RVR of ceramics in configurations 1 (free) and 2 (glued).

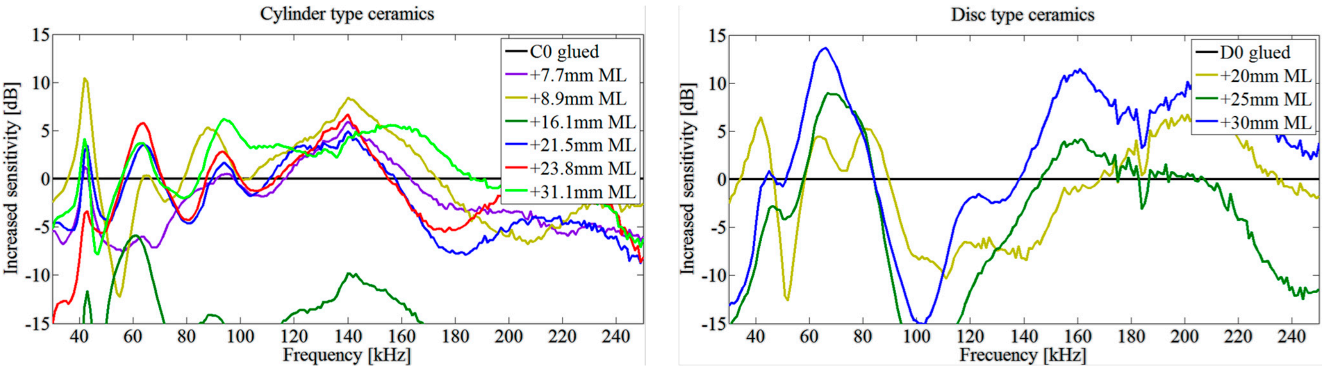


Figure 5. Difference of sensitivity in ceramics glued to the vessel, with and without ML.

7. Summary and Conclusions

With respect to the study of obtaining the piezoceramic coefficients, the measured and simulated results agree with the expectations except for the case of the measured cylindrical geometry. Although the geometrical requirements of the standard ($L/D > 2.5$) were fulfilled, the deviation may be due to the fact that the cylinder is not long enough to vibrate adequately in the mode 33. Some authors [6] consider this ratio insufficient and propose a larger length of the cylinder. Despite this, we can conclude that the method has been properly implemented and we are able to get the full set of piezoelectric coefficients with this method.

The effect of matching layers in sensitivity has been measured using two configurations (free and glued). Placing the ceramic in the vessel increases, in general, the sensitivity due to a best impedance matching system (water-vessel-ceramic) than for the water-ceramic case. This is an intrinsic acoustic gain for the characteristic setup in bubble chambers. When we add an intermediate ML, additional increased sensitivity peaks can be obtained. This improvement can reach 10 dB. Finally, in the expected frequency of the maximum sensitivity frequency study, the experimental values agree quite well to the theoretical first peak, especially in the case of cylinders since the transmission behaves according to a plane wave, necessary condition to apply the model. As a final summary of the work, we can conclude that the analytical model can be useful to select the ML material and length in order to increase the sensitivity of the ceramics glued to the vessel in PICO detectors. The results can easily be generalised to different applications with acoustic detection through walls or layers.

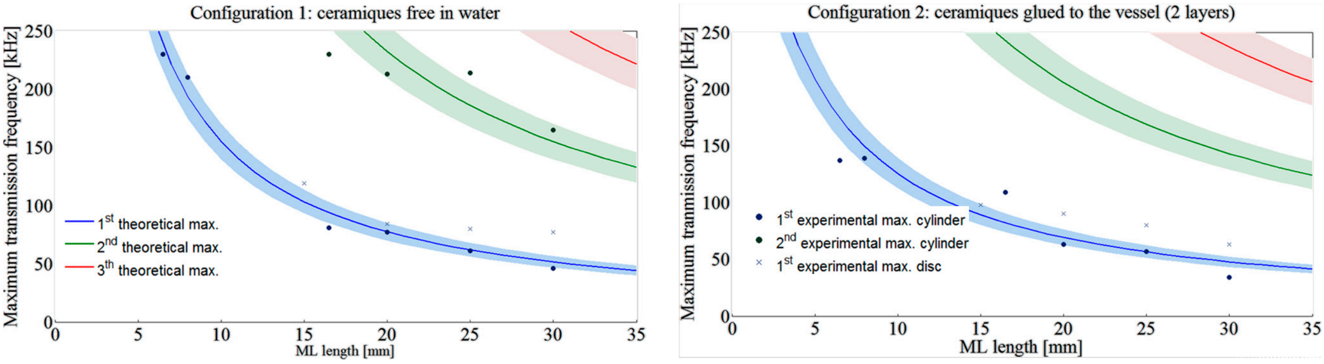


Figure 6. Frequency of maximum sound transmission vs. thickness of the aluminium layer for the models of transmission of 1 layer (left) and 2 layer (right), compared to the measured data.

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Conflicts of Interest

The authors declare no conflict of interest.

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