

CHARACTERIZATION OF PIEZOELECTRIC ACTUATORS USED FOR SRF CAVITIES ACTIVE TUNING AT LOW TEMPERATURE

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Abstract

Superconducting RF (SRF) cavities are very sensitive to small mechanical perturbations due to their narrow bandwidth. High electromagnetic fields induce mechanical deformations in the micron range leading to a frequency detuning of the same order of magnitude of the bandwidth of these accelerating structures [1]. In order to reduce this effect, which results other ways in a substantial additional RF power so as to control the electromagnetic fields, the SRF cavities are stiffened. However, the detuning factor reached with stiffened SRF cavities is still much higher than needed. An alternative strategy or dynamic compensation of Lorenz Force detuning based on commercial piezoelectric actuators was proposed recently and the principle was demonstrated on TESLA cavities [2]. A piezo-tuning system is actually developed at IPN Orsay for high intensity proton linacs SRF cavities. A dedicated facility was designed and successfully used for the characterization of piezoelectric capacitive actuators at low temperature (i.e 1.8 K-300K). This device is described and the first experimental results (i.e piezoelectric actuator calibration or displacement DX vs. applied voltage V , capacitance C_p vs. T dielectric properties vs. T and frequency) are analyzed and discussed. The experimental data show that the full range displacement DX of the actuator decreases strongly with T . For the actuators studied, the variations of dielectric losses with T for a sine displacement of given amplitude ($1\mu\text{m}$) show a maximum around 10 K-20 K leading to a thermal load lower than 1 mW at 1.8 K for a sinusoidal displacement of 1 micrometer at a frequency of 100 Hz

EXPERIMENTAL SET UP AND TEST PROCEDURE

Test cell description

The actuator tested, consist of piezostacks (multilayer: 350 disks of $100\ \mu\text{m}$ thickness, material: Lead Zirconate Titanate or PZT) without housing and no preload (Fig. 1).

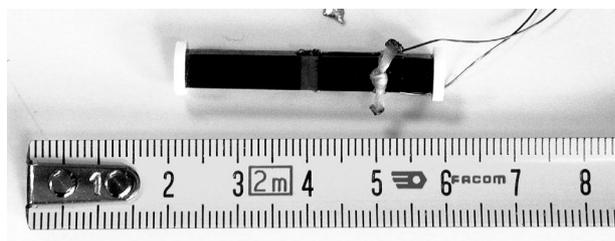


Figure 1: Piezoelectric actuator (material: PZT).

The apparatus dedicated to the tests of the actuators must fulfill the following main requirements:

- calibration and full characterization of piezoelectric actuator under vacuum and at controlled low temperature T (1.8 K – 300 K),
- avoid shear forces and torsional forces to the actuator,
- allowing mechanical pre-loading to the actuator for dynamic operation.

Two test-cells were used for the experiment. A schematic diagram and a photograph of the first test-cell developed are shown in Fig. 2 and Fig. 3. The actuator is clamped between two Stainless Steel (SS) cylindrical supports (diameter $\Phi 20$, thickness: 10 mm) then inserted into a special holder. The holder includes three SS main flanges (diameter: $\Phi 82$, thickness: 15 mm), Belleville rings acting as springs and supporting rods ($\Phi 12$). The actuator supports are attached to the main flanges via small SS balls ($\Phi 6$) in order to avoid shear and torsional forces, which would damage the piezostacks.

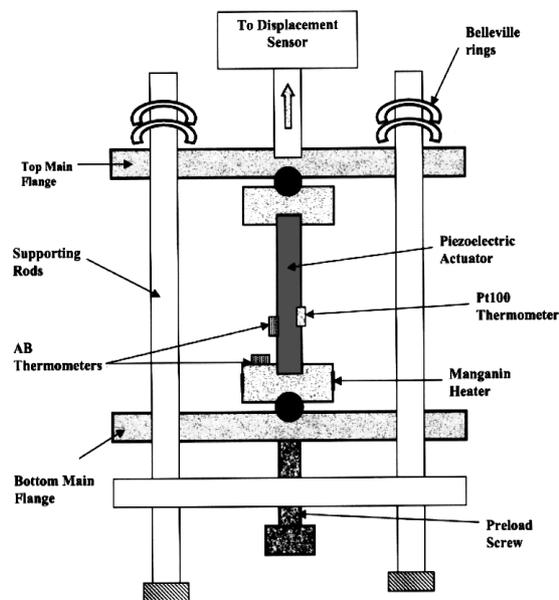


Figure 2: Diagram of the Test-Cell.

Moreover, in order to increase the tensile strength of the piezostacks during dynamic operation, a bronze screw acting axially on the lower flange allows the adjustment of the actuator preload (up to $\sim 10\%$ of the maximum preload $F_{\text{max}}=1\ \text{kN}$). The whole assembly is enclosed in a vacuum chamber. Notice that the bottom extremities of

the three supporting rods are rigidly fixed to the chamber. Furthermore three calibrated thermometers (platinum resistor, Allen-Bradley carbon resistors and cernox resistors) and a manganine heater are used to control and measure the piezostacks temperature. Finally a mechanical system including SS rod ($\Phi 14$) and bellows allows the transmission of the motion induced by the actuator to a potentiometric displacement sensor operated at room temperature.

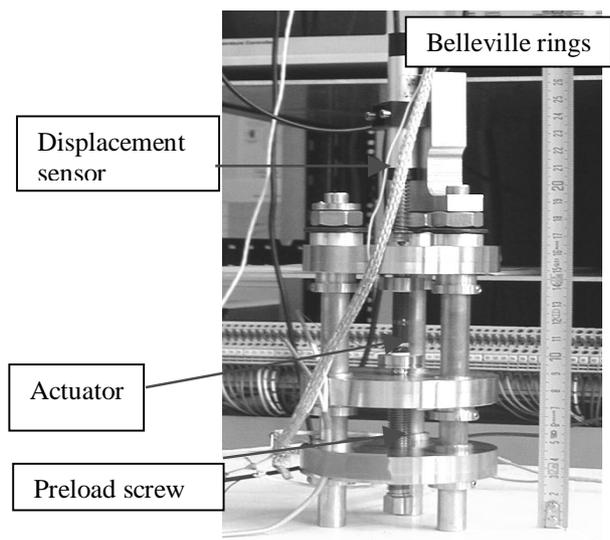


Figure 3: Test apparatus prior to installation into vacuum chamber (First test-cell).

The first test-cell has a main drawback: it takes a too long time to cool down. This is due to the large thermal capacity of SS part of the system (supporting rods and main flanges). So we developed a second test-cell (Fig. 4), which consist mainly in a cylindrical vacuum chamber with a removable thin end plate. The actuator is sandwiched between the lower rigid flange (thickness: 32.5mm) and the upper thin SS sheet (thickness: 0.2mm). The system include SS ball with special fixture to avoid shear and torsional forces on the piezostacks, which is equipped with a heater and calibrated temperature sensors. When a voltage is applied to the piezoactuator, it expand leading to a deformation of the upper thin sheet, the resulting motion is transmitted to the displacement sensor at room temperature via a $\Phi 14$ SS rod.

Experimental procedure

Prior to the low temperature tests, the displacement sensor is calibrated at $T \cong 300$ K using the piezoelectric as a reference and the manufacturer calibration data (i.e displacement vs. actuator voltage). The low temperature tests were performed in the temperature range $T = 1.8$ K-300 K using either LN_2 or Lhe as refrigerant. The test-cell

is evacuated to 10^{-5} mBar then cooled down to 77 K or 4.2 K. A thermal switch is used to improve the cooling rate in the case of the first test-cell: the chamber was pressurized up to 200 mBar with high purity helium.

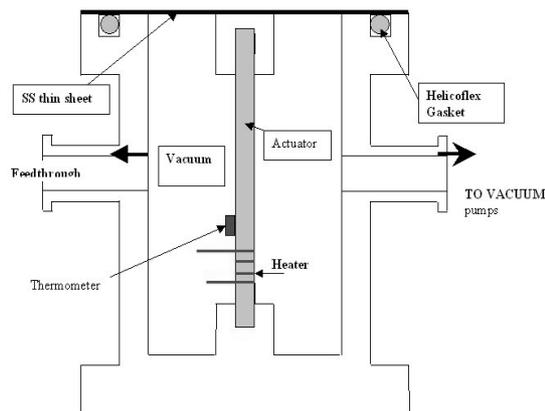


Figure 4: Diagram of the second test-cell

Notice that the thermal switch is only used for temperatures higher than 80 K. Once the piezostacks actuator is at LN_2 or Lhe normal boiling point temperature, the test-cell is evacuated ($\sim 10^{-5}$ mBar). The actuator temperature T is then regulated at the desired value and measurements are performed. In the course of the experiments, several parameters were investigated: a) displacement versus voltage characteristics at different temperatures, b) actuator capacitance C_p vs. T , c) dielectric properties (dielectric constant: ϵ_r , and loss tangent: $tg(\delta)$) as function of T using a LCR meter, d) heating ΔT due to dielectric losses as function of the frequency f and amplitude V of the sinusoidal signal applied to the piezostacks at different temperatures.

RESULTS AND DISCUSSION

Several low voltage piezostacks of different productions series fabricated by JENA PIEZOSYSTEM company were tested. Some of these actuators show electrical breakdown during the tests. As illustration, we present in Figure 5, the response (sensor signal) of the displacement sensor to voltage applied to the actuator #8114 at $T = 295$ K: the sensing current in the displacement sensor is 40 μA .

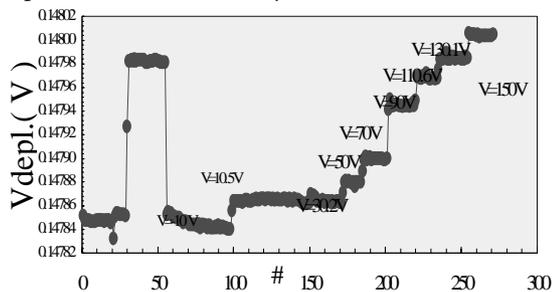


Figure 5: Displacement sensor signal versus applied increasing voltage: Actuator #8114.

Notice that each stage in the curve of Fig. 5 corresponds to the indicated voltage (label).

Reproducibility tests at Room Temperature (RT)

Reproducibility tests were performed on the actuator #8114 at T=295 K while increasing the applied voltage from -10V to 150V (full range). The corresponding data are presented in Fig. 6.

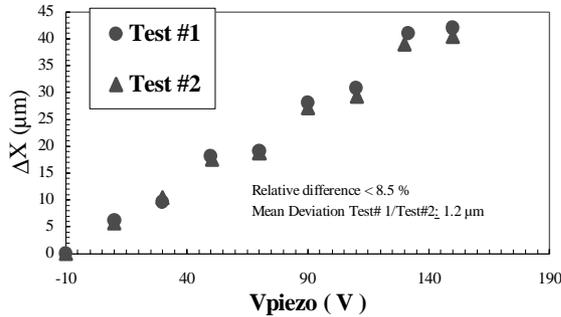


Figure 6: Reproducibility tests at T=295 K-Actuator #8114.

The full range displacement at T=295 K is 42.1 μm. The observed difference is attributed to mechanical hysteresis in the system and measurement errors: the mean standard deviation between the two tests is 1.2μm and the relative difference is less than 8.5%.

Calibration: displacement versus actuator voltage at different temperatures

a) Actuator # 8114

The displacements versus actuator voltage characteristics were measured at different temperatures T between 77 K and 300 K. The response of the actuator #8114 at 77 K is presented in Fig. 7. As expected, the displacement at a given actuator voltage decreases with T.

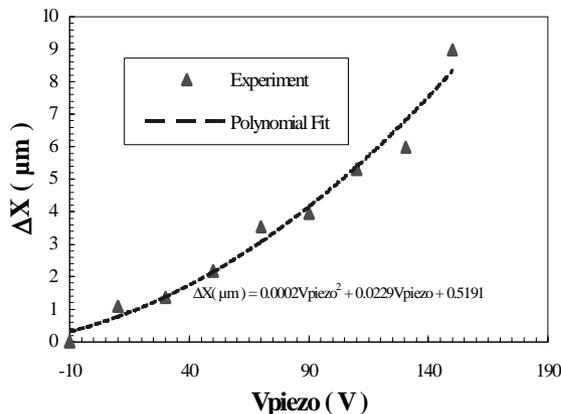


Figure 7: Displacement versus actuator voltage at T=77 K (actuator#8114).

This is mainly due to the decrease of the capacitance with T. The full range displacement is decreased by a factor of ~ 4.7 when T decreases from 300K down to 77K and this result is in the range of data reported previously by other authors [3-4]. Moreover, the variations of the full range displacement or maximum actuator expansion ΔX with temperature are shown in Fig. 8 for the same actuator # 8114. The slope of the curve ΔX vs. T curve decreases strongly with temperature. This behavior seems to be mainly due to the strong dependence of the actuator

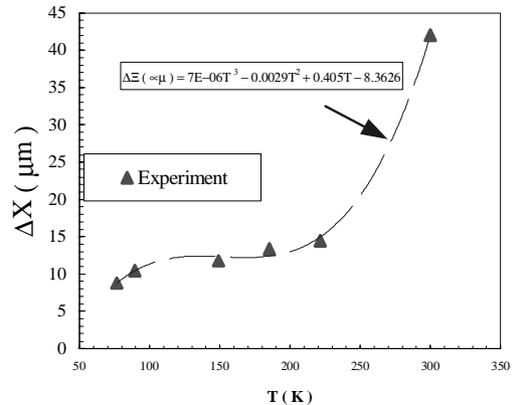


Figure 8: Variations of the full range (V_{max}=150 V) displacement with temperature (piezo #8114).

capacitance on temperature as we will show later in this paper. Unfortunately this actuator was breakdown (electrical breakdown) at the end of these first tests.

b) Actuator # 9221

This actuator is from a second series. As we have no data for temperature lower than 77 K, we performed first experiments in liquid helium. These tests allow us to measure the full range displacement ΔX for temperatures 1.8 K ≤ T ≤ 52 K (Fig. 9). Note that at R.T the manufacturer calibration data gives ΔX=42.6 μm.

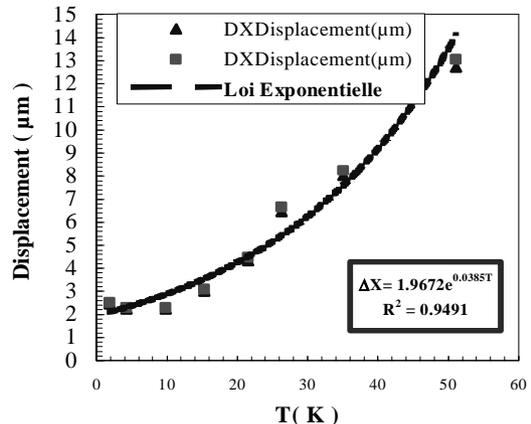


Figure 9: Full range (V_{max}=150 V) displacement at low temperature for actuator #9221.

The two sets of experimental data of Fig. 9 correspond to 2 calibrations at R.T showing a relative variation less than 2.7%. Moreover these results show that the maximum actuator expansion depends exponentially on temperature. Finally, for $T \leq 10$ K the maximum displacement is nearly constant: the observed variations are in the range of experimental errors.

Dielectric properties

In the course of the experiments, we measured by a LCR meter, the dielectric properties (capacitance, loss tangent) of the actuators at three frequencies (100Hz, 120 Hz and 1kHz). However only data at $f=100$ Hz will be presented in this paper. For the actuators #8114 and #9220, the measurements were performed for T ranging from R.T down to 90 K while for the actuator #9221, these measurements were performed at R.T and in the range 1.8 K-52 K.

a) Capacitance and dielectric constant versus T

The variations of the actuator capacitance with temperature are presented in Fig. 10 for the three actuators tested.

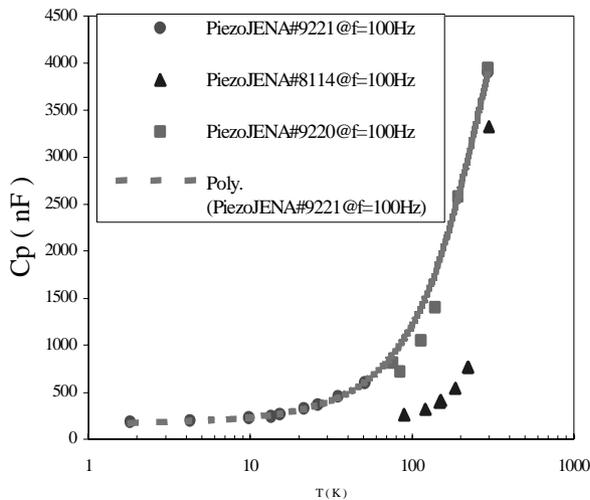


Figure 10: Capacitance versus T for three actuators.

The capacitance decreases dramatically from ~ 3900 nF at R.T to ~ 180 nF at 1.8 K (actuator #9221). The piezostacks of the same production series (#9220 and #9221) have nearly the same temperature dependence and their values are close together. On the other hand, the actuator #8114 of another production series have a quite different behavior: its capacitance depend more strongly on temperature leading to a lower full range displacement. Consequently, if piezostacks of different production series are used, a careful individual calibration (ΔX vs. T) is needed. Moreover, at low temperature (i.e. $T \leq 52$ K), the full range displacement is proportional to the actuator capacitance as shown in Figure 11: it decreases down to

its value at $T \sim 10$ K (for $T < 10$ K ΔX is nearly constant to within experimental errors: see Fig. 9).

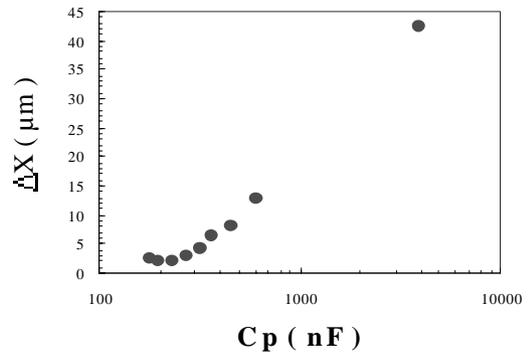


Figure 11: Full range displacement versus capacitance (actuator #9221).

The results of Figure 11 are very important: it might give another mean and a more simple way to calibrate actuators but more statistics are needed (i.e. calibration and C_p vs. T measurements) to confirm this behavior (i.e. $\Delta X \propto C_p$). Notice that capacitance measurements are more simple and less time consuming, as compared to a true calibration (i.e. Displacement versus voltage applied to actuator at different temperature). The actuator consist of $n=350$ thin layers (thickness $e=100$ μm) of electroactive ceramic material (PZT) electrically connected in parallel. The capacitance is then given by the well-known expression:

$$C_p = \frac{n \cdot \epsilon_0 \cdot \epsilon_r \cdot A}{e}$$

With:

- ϵ_0 : permittivity of vacuum,
- ϵ_r : dielectric constant of the material,
- $A=25\text{mm}^2$: electrode surface area.

Using the above expression and experimental data C_p vs. T, we calculated the variations of the dielectric constant as function of temperature. Obviously, the results shown in Fig. 12 are similar to C_p vs. T curves.

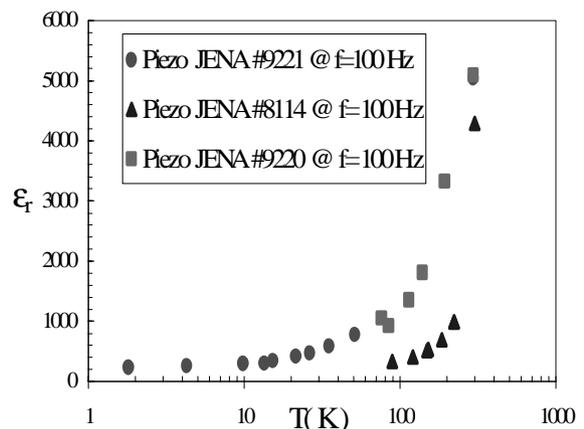


Figure 12: Dielectric constant vs. T for three actuators.

b) Loss tangent and dielectric losses

The measured loss tangent of the three actuators tested are presented in Fig. 13. In contrast to the parameters C_p and ϵ_r , the loss tangent did not show a monotonous dependence as function of temperature: from its R.T value, $\text{tg}(\delta)$ increases as T is decreased then reach a maximum (peak) around $T \approx 50$ K, afterwards it decreases as T is lowered down to 1.8 K.

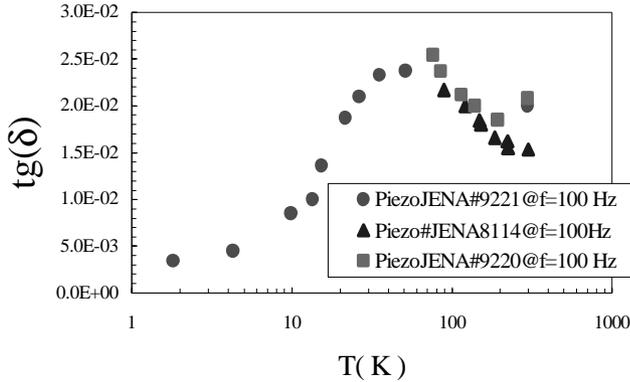


Figure 13: Variations of loss tangent with temperature.

More investigation is needed to understand the loss tangent behavior of this material. However, this parameter reaches its minimum value ($\text{tg}(\delta) = 3.45 \cdot 10^{-3}$ at $T = 1.8$ K for $f = 100$ Hz) in the range of temperature of interest for SRF cavities ($T \leq 4.5$ K).

From the above results (calibration, C_p vs. T and $\text{tg}(\delta)$ vs. T), we calculated the total dissipated power due to dielectric losses as function of temperature (Fig. 14) for a sinusoidal motion of $1 \mu\text{m}$ amplitude of the actuator operating at a frequency $f = 100$ Hz.

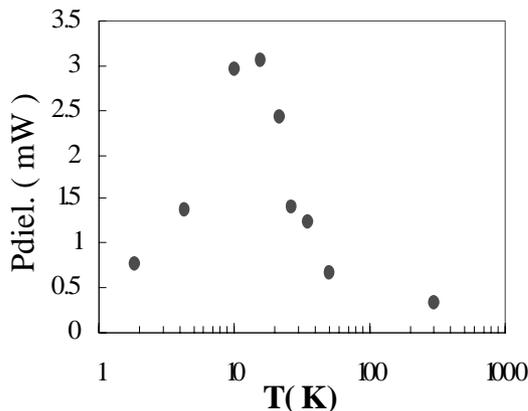


Figure 14: Total dielectric losses for a sinusoidal motion of $1 \mu\text{m}$ amplitude at 100 Hz.

These calculations are based on the operation of $\beta = 0.65$, $f = 704$ MHz five cell cavities [5] which will be used in high intensity proton linac [6-8]. For these cavities a longitudinal deformation of $1 \mu\text{m}$ corresponds to

a theoretical frequency variation of 250 Hz. These results clearly show that dielectric losses of such actuators (piezostacks volume: 900mm^3) operating in the above conditions are very small ($\leq 1 \text{mW}$).

When the actuator is subjected to a sinusoidal voltage of amplitude V and frequency f, the total dielectric losses P_{diel} are given by:

$$P_{\text{diel}} = \pi \cdot f \cdot C_p \cdot V^2 \cdot \sin(\delta)$$

We measured the heating due to dielectric losses at different temperatures in two different conditions: a) at a given fixed voltage amplitude V (sinusoidal signal) and variable frequency f, b) at a given frequency and variable voltage amplitude. A typical result illustrating the first case is presented in Fig. 15.

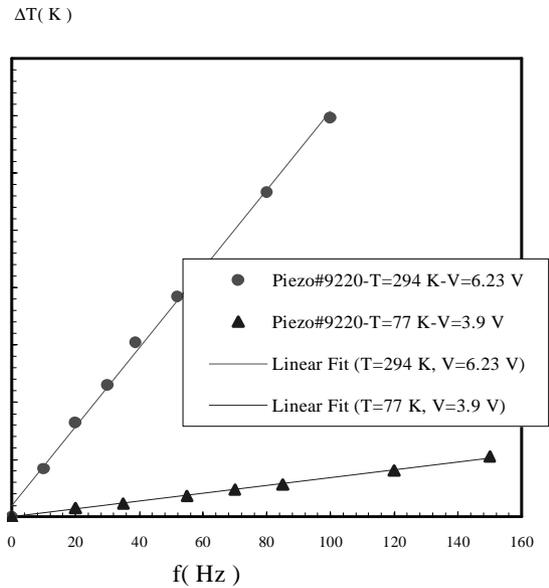


Figure 15: Heating due to dielectric losses : effect of signal frequency.

The measured heatings clearly show a linear dependence on frequency at two temperatures (294 K and 77 K), in good agreement with the above formulae ($\Delta T \propto P_{\text{diel}} \propto f$). Furthermore, for the two modulation voltages used in these tests and $f = 100$ Hz, the ratio of the measured heating respectively at $T = 295$ K and $T = 77$ K is ≈ 10.3 and this value is very close to the ratio (≈ 10.1) of the dielectric losses as given by the above formulae at these two temperatures. This agreement is obviously observed at the other frequencies because the results clearly show the linear dependence of P_{diel} with respect to f. The effect of the voltage amplitude on the heatings was measured at $T = 77$ K and $f = 101.5$ Hz with the actuator #8114. The observed heatings as function of the square of the voltage amplitude are shown in Fig. 16. These results confirm the quadratic dependence of dielectric losses on the voltage at least for small heating ($\Delta T \leq 2$ K, $V \leq 2.1$ V).

The observed departure from the quadratic dependence at higher voltage could be attributed to nonlinear effect resulting from C_p and $\sin(\delta)$ which depend on temperature.

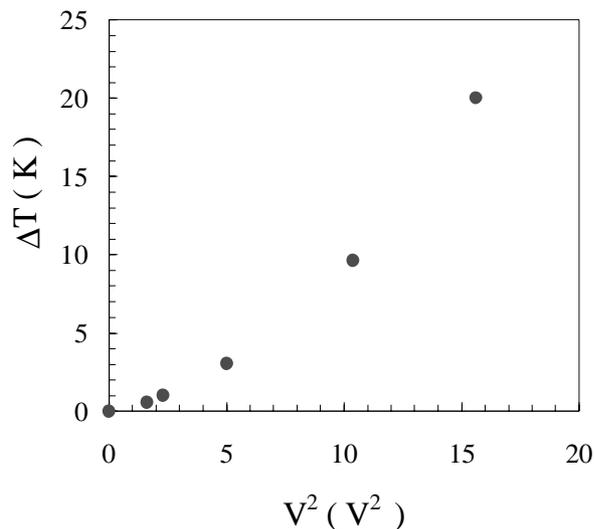


Figure 16: Heating due to dielectric losses: effect of voltage amplitude.

CONCLUSION

A dedicated apparatus was developed for characterization of piezoelectric actuators at low temperature. Several piezostacks were successfully tested: the full range displacement and dielectric properties of these actuators were measured as function of temperature. The measured parameters show variations from a series production to another. The full range displacement ΔX decreases strongly with temperature from $\sim 42 \mu\text{m}$ at R.T down to $2.3 \mu\text{m}$ at 1.8 K. Notice that at $T \leq 10 \text{ K}$, ΔX is nearly constant. The dielectric losses for a sinusoidal displacement of $1 \mu\text{m}$ amplitude at 1.8 K at a frequency of 100 Hz are lower than 1mW. These actuators will be integrated in a cold tuning system for a 704 MHz, five cells SRF cavity and tests will be performed in the horizontal cryostat CRYHOLAB. Dynamic compensation of Lorentz force detuning as well as vibrations and microphonics will be investigated. Finally irradiations tests with neutrons of piezoelectric actuators at low temperature are planned in the future.

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