Electromechanical characterization of piezoelectric actuators subjected to a variable preloading force at cryogenic temperature

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Abstract

A dedicated apparatus was designed and constructed for studying the electromechanical behavior of prototype piezoelectric actuators subjected to a variable preloading force at cryogenic temperatures. This device was successfully used for testing a piezoelectric actuator of PICMA type from PI™, for T in the range 2 K-300 K. The dielectric properties as well as dynamic properties were measured including the actuator characteristics when used as force sensor. The corresponding data are reported and discussed.

Introduction

Piezoelectric actuators, which are integrated into the cold tuning system [1-2], will be used to compensate [3-4] the small mechanical deformations of the cavity wall induced by Lorentz forces [5] for accelerating gradients up to 35 MV/m. In order to provide for a reliable operation of the accelerator, the piezoelectric actuators (~30.000-40.000 units for ILC[1] [6]) should function satisfactorily for a period close to machine life duration (~20 years). The corresponding actuator lifetime requirements should be much higher than $3.2 10^9$ cycles (pulsed mode, repetition rate: 5 Hz). Moreover, previous studies showed that the life time of piezostacks depends strongly on the applied preloading pressure P_{Load} (Fig. 1) with an optimum value $P_{Load} \sim 10 MPa$ at T=300 K. On the other hand, the actuator displacement versus preloading pressure characteristics (Fig. 1) is no monotonic: the maximum displacement is observed for P_{Load} in the range 20MPa- 50 MPa [7]. Further, the lifetime versus preload curves depends strongly on actuator material and fabrication process. Due to the lack of data for the operating conditions in the actual tuner (i.e. under vacuum and cryogenic conditions), it is necessary to perform an experimental investigation of electromechanical behavior of actuators subjected to axial preload at cryogenic temperature.
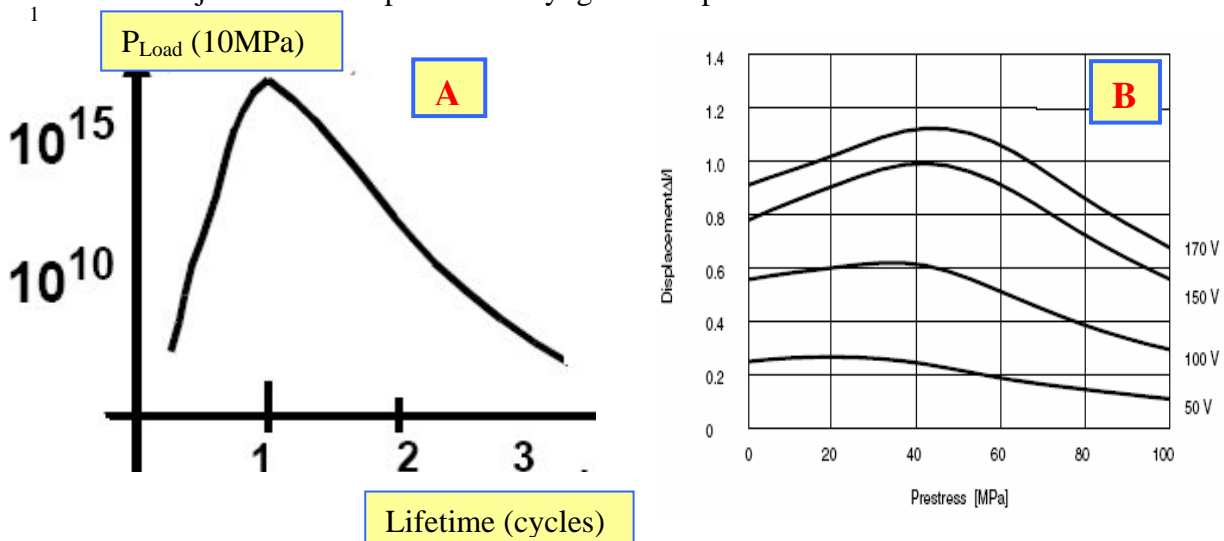
Fig. 1: A) Sketch of lifetime versus preloading pressure, B) Displacement versus preloading pressure at different voltages *(R. Binding et al., see ref. 7)*.

Description of low temperature preload experiment

The main goals of low temperature preload experiment are:
1) Study the effect of a variable and controllable axial preload on the electromechanical properties of the piezoelectric actuator (stroke, capacitance, loss factor, impedance, etc),
2) Development of a procedure for applying, adjusting and controlling the preload,
3) Study of the behavior of piezostacks as force sensor,
4) Measurement of the mechanical stiffness of the actuator,
5) Study the actuator resonance spectrum versus preload.

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[1] ILC : International Linear Collider, previously TESLA (TeV Energy Superconducting Linear Accelerator)

Experimental set-up

Principle of experiment and mechanical design

The apparatus should allow to applying and measure a controlled and adjustable axial force in the range 1kN- 4kN to the piezoelectric actuator. Moreover, the piezoelectric actuator should be subjected to this force in an environment similar to the operating conditions in the tuner namely under vacuum (pressure$<10^{-5}$ mbar) and at cryogenic temperatures. We have designed and constructed a device dedicated to low temperature preloading experiment. The simplest way for applying a vertical downward compressing force is naturally to use gravity. But due to the relatively high value (~100 kg) of the mass (in case of direct load on the actuator axis) needed for achieving force of ~1kN, it is obvious that a lever arm system with a magnification factor ~10-15 (lever arms ratio) should be used. The operating principle of the method is presented in Fig.1. The piezostacks to be tested is enclosed in a stainless steel vacuum chamber which will be immersed in a liquid helium bath. A rotating arm located at room temperature (T~300 K) outside the cryostat allows applying a vertical force (along the actuator axis) to the piezostacks via a high stiffness transmission rod. The preloading force applied to the actuator is simply adjusted by varying the load at the extremity of the rotating arm. At the mechanical equilibrium, the sum of the momentums of all the forces is equal to zero. Assuming a negligible friction on the rotation axis, the preloading F force is simply given by the law of conservation of angular momentum:

$$F \;=\; Fc \cdot \left(\frac{L_C}{L_P} \right) + m_A \cdot \left(\frac{L_A}{L_P} \right) \cdot g \qquad (1)$$

Where m_A is the masse of the rotating arm, L_P, L_A and L_C are respectively the distances from the rotation axis of the piezostacks axis (L_P), the center of mass of the arm (L_A) and the loading mass(L_A) and g the gravity constant.

Taking into account the available space on the upper flange of the cryostat insert, which support vacuum pumps and other components, the values of the lengths L_P, L_C are respectively 30mm, 430mm leading to a lever arm ratio r=L_P/L_C =14.66. The key element of the preloading is the rotating arm; consequently it was carefully designed using Finite Element Method numerical simulations in order to verify that it behaves as a rigid body. Note that the simulation model includes the transmission rod and the actuator. The different arms studied and the main results concerning their mechanical behavior are listed in Table 1.

Cross-section Shape	Dimensions (mm^3)	Material	ΔXp (μm)	ΔXc (μm)	ΔXc /ΔXp	Bend (μm)
rectangle	40x10x500	Aluminum	66.1	27490	416	26521
Rectangular tube (2mm wall thickness)	20x20x500	Aluminum	66.4	12379	186	11406
square	45x45x500	Stretched steel	59.4	913	17.7	42.5

Table 1: The rotating arms studied (ΔXp and ΔXc are respectively the vertical displacements on the piezostacks axis and at the masse location)
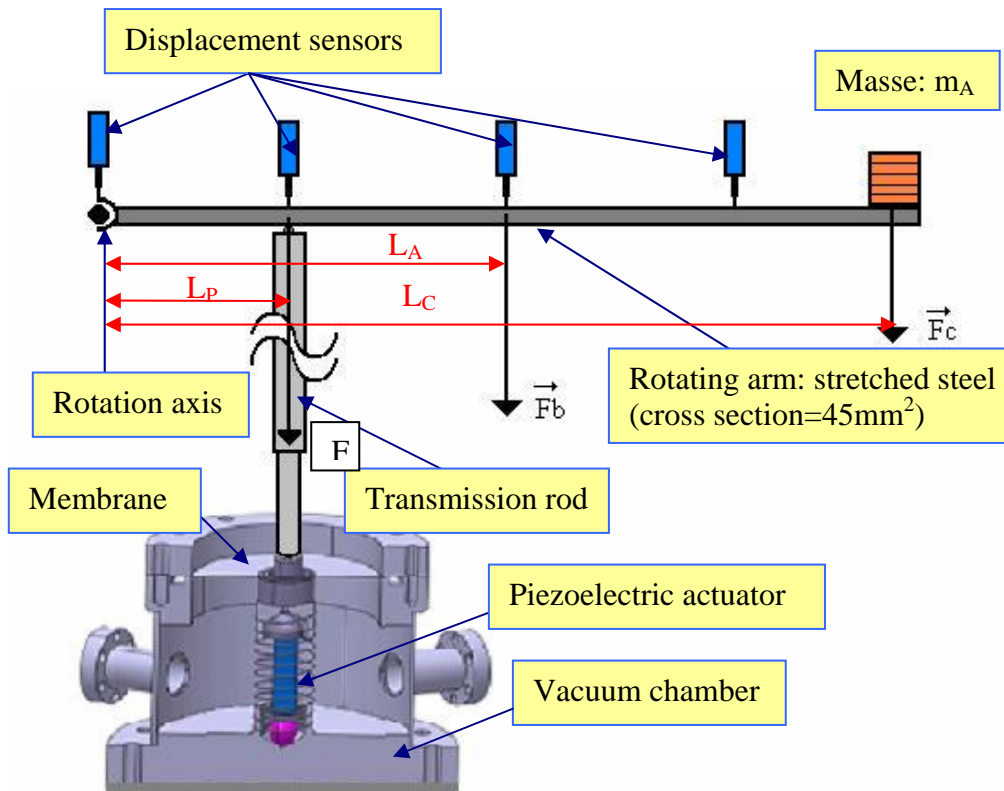
Fig.1 : Sketch of the experimental method

The computed displacements for the square shape cross-section arm made of stretched steel are shown in Fig. 2. These results leads to a ratio $\Delta Xc/\Delta Xp = 17.7$ of the vertical displacements at the masse location and along the piezostacks axis respectively, which is close to the value of lever arm ratio $r = L_P/L_C = 14.7$. The relative difference (i.e. 20%) is due to the finite rigidity of the arm. As expected, due to their low stiffness, the first two arms of rectangular shape and made of aluminium these two arms don't behave as a rigid body. More precisely, they show a high deflexion or bending leading to a ratio $\Delta Xc/\Delta Xp$ one order of magnitude higher than the target $r = 14.7$.
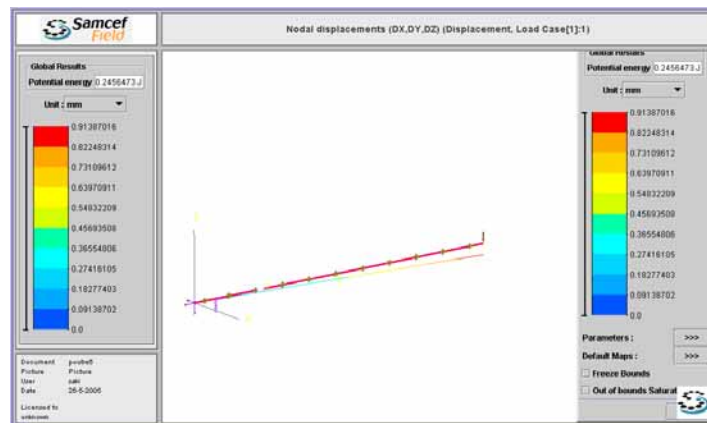

Fig. 2: Computed displacements of the square shape cross-section arm made of stretched steel

The test-cell [8-10] is placed inside the cryostat (diameter: Φ350, height: 1500mm?) while the rotating arm and the displacement sensors are located outside the LHe vessel at room temperature. The preloading force is transmitted to the piezostacks via a transmission rod equipped with a stainless steel bellow at its upper extremity. The transmission rod should fulfil two main requirements: 1) stiffness higher than 25 N/µm, 3) conduction heat load from T=300 K to the liquid helium (LHe) bath (T=4 K) lower than 750 mW for 1m length. A stainless steel tube or a bare rod could be used (Table 2). These results show that a 16mm diameter bare rod fulfils the above requirement with minimum heat load to Lhe.

Geometry	Stiffness (N/µm)	Heat load (mW)
bare rod-Diameter: 16 mm	26	615
Tube Diameter: 38mm, Thickness: 2 mm.	30	731

Table 2: Mechanical and thermal characteristics of two possible transmission rods.

Moreover the upper extremity of the transmission rod is connected to a stainless bellow at room temperature (Fig. 3). The buckling force for the first rod (diameter: Φ_1 =6mm, length L_1=90mm) used for previous tests (i.e. without preloading force) is F_B=3.9 kN in the ideal case (i.e. no defect in the material or welding). For the safety of the people, the rule for cryostat design a factor 3 (safety margin) is needed. Consequently this rod should be changed in order to fulfil this requirement, namely $F_B > 3.F_{max}$= 12 kN (F_{max}= 4kN: maximum preloading force). An 8 mm diameter stainless steel connecting rod, which fits in the actual bellow, satisfies this criterion (e.g., F_B=12.2 kN).
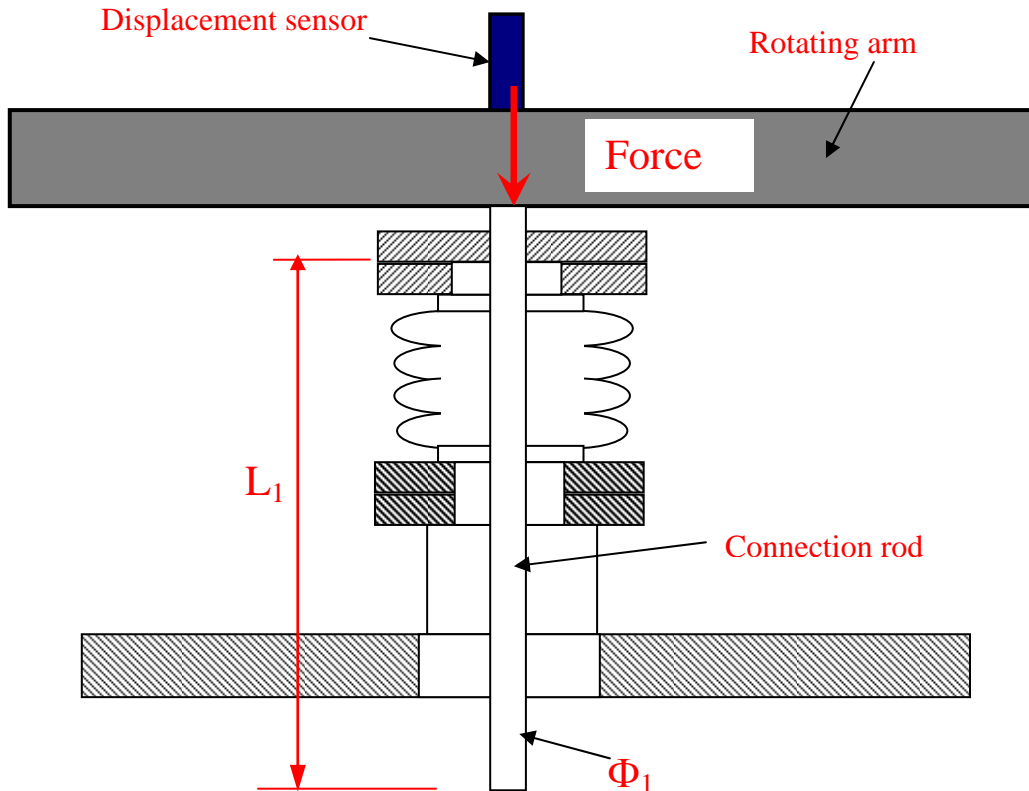

**Fig.3 : Connection of the transmission rod to the bellow.**

Description of the apparatus

The test-cell [8-10], illustrated in Fig. 4a and Fig. 4b, consists mainly in a cylindrical vacuum chamber with a removable thin end plate. The actuator, which is housed in the chamber, is sandwiched between the lower rigid flange (thickness: 32.5mm) and the upper thin stainless steel (SS) sheet (thickness: 0.2mm). A special fixture based on a sphere and cone system was used to avoid shear and torsion forces on the piezostacks. Two stainless steel pieces are glued at the two extremities of the piezostacks: hemispherical holder at the upper extremity and thin cylinder with conical grove at the lower extremity. Further, the actuator is equipped with a heater (manganin wire) and a calibrated thermometer [11] (CERNOX resistor) in order to vary and control the piezostacks temperature. The thermometer allows also the measurement of the heating due to dielectric losses. The operating principle of this device is the following:

1) Actuator mode: a voltage is applied to the piezoactuator which expand leading to a deformation of the upper thin sheet; the resulting motion is transmitted to the displacement sensors at room temperature via a Φ16 stainless steel rod.
2) Force sensor mode: a loading force is applied to the piezostacks via de transmission rod and the response of the actuator (i.e. capacitance and transient voltage) is measured.
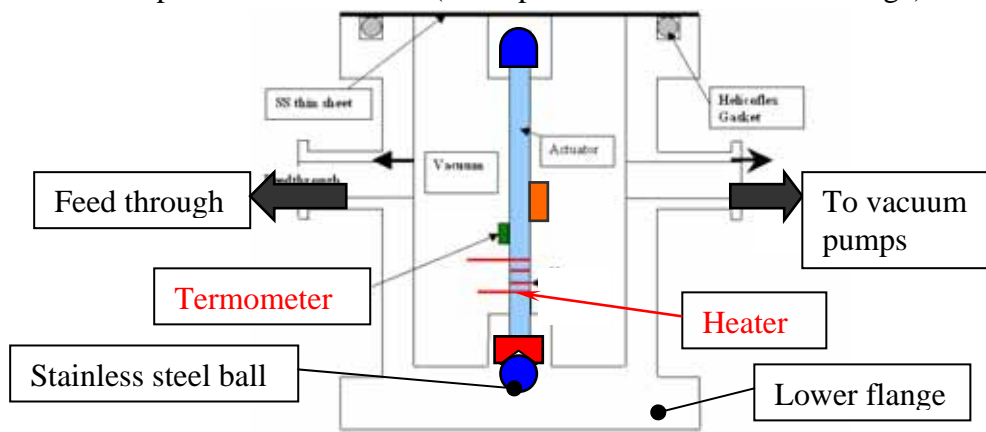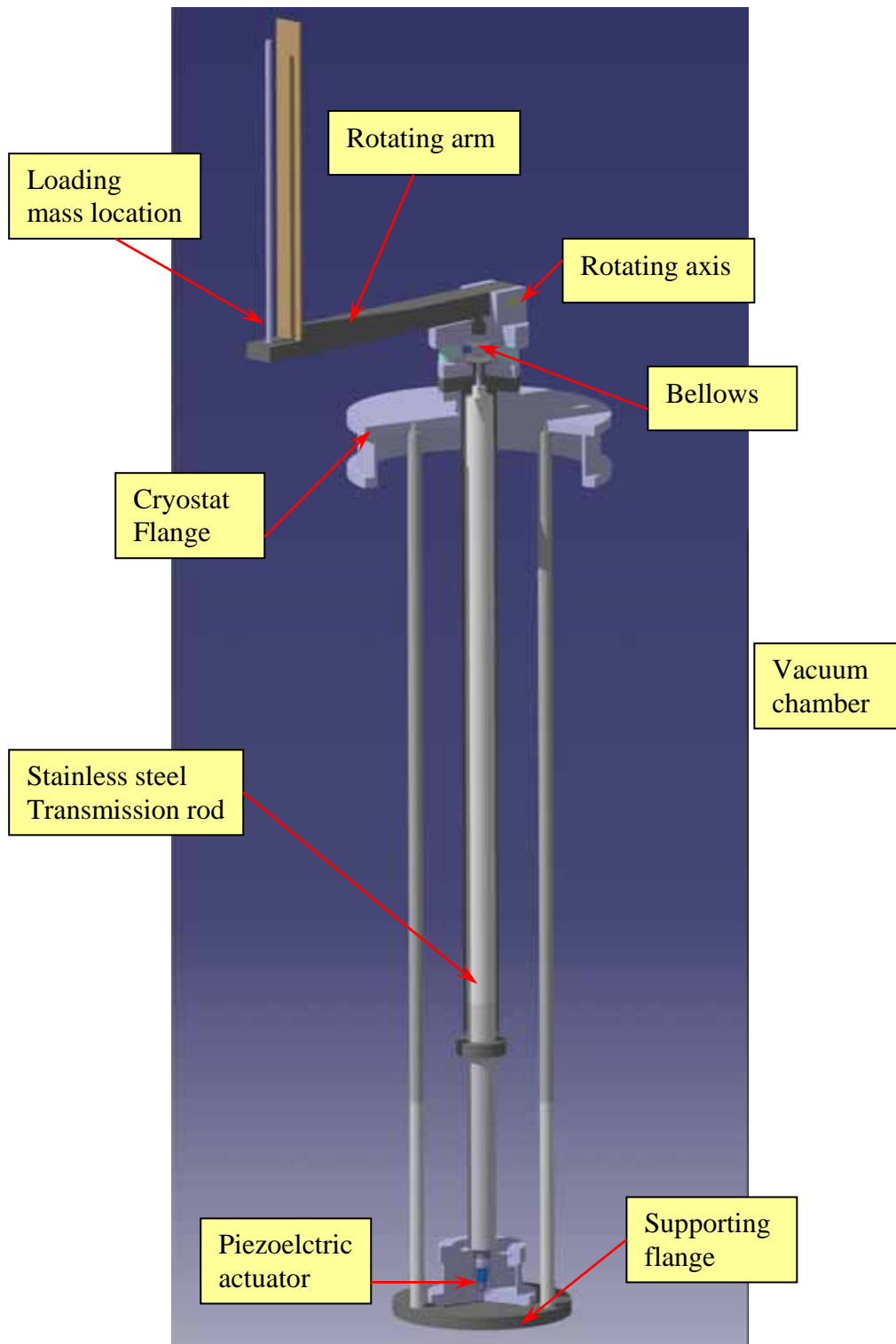

Fig. 4a: Diagram of the test-cell
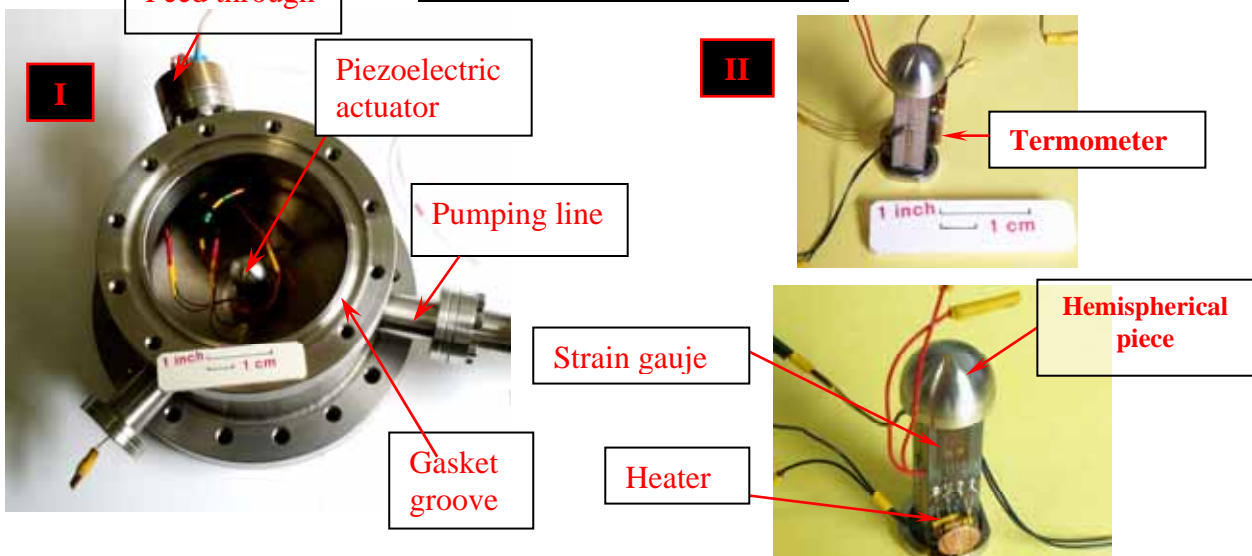
Fig. 4b: I) Test-cell with piezoelctric actuator during preparation, II) Piezoelctric actuators equipped with heater and a calibrated thermometer

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After the preparation of the chamber (e.g., instrumentation, leak tests), the test-cell is mounted on the insert (Fig. 5) which is placed into the cryostat for the tests at cryogenic temperature.

**Fig. 5: 3D view of the insert dedicated to preloading experiment**

A close view of the upper part of the insert showing the rotating arm, the vacuum pumps is presented in Fig. 6. The block diagram of the data acquisition system is illustrated in Fig. 7.

Fig. 6: Photograph of the upper part of the insert ready for cryogenic test

Experimental procedure

The block diagram of the data acquisition system is illustrated in Fig. 7.
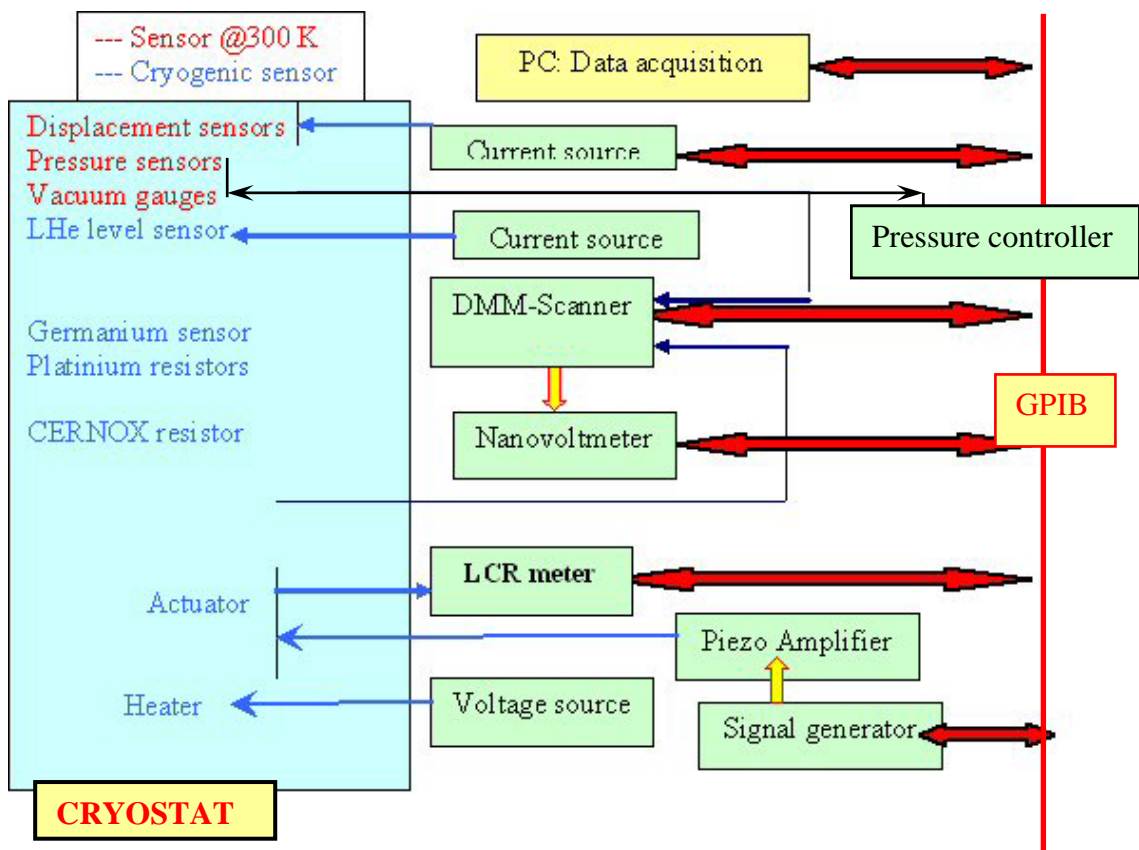
**Fig. 7: Block diagram of the data acquisition system**

Prior to the low temperature tests, the test-cell is evacuated to $P_v < 10^{-5}$ mBar and we proceed to the calibration of all the displacement sensors are calibrated at $T \cong 300$ K using the piezoelectric as reference and the manufacturer calibration data (i.e., displacement vs. actuator voltage). This calibration is performed for different values of the preloading force F. The vessel (cryostat) is filled with Liquid helium in order to cool down the system to 4.2K (Normal boiling point of helium) the test-cell. The bath temperature T_{bath} is then decreased simply by reducing the vapor pressure of the system P_{bath}, which is kept constant during all the tests: P_{bath} (e.g., $T_{bath} = 1.8$K) is set to 16 mbar and stabilized by means of a DIP pressure controller. The cryogenic tests are performed in the range T= 1.8K-300K. Using the heater, the actuator temperature T is then regulated at the desired value and the measurements are performed. In the course of the experiments, we performed the following measurements [8-10] at a given temperature and for different values of the preloading force F:

1) Displacement versus voltage characteristics (e.g., calibration),
2) Dielectric properties of the actuator (e.g., capacitance: Cp, dielectric constant: ε_r, loss factor: tg(δ), complex impedance: amplitude (Z) and phase (θ)) using the LCR meter,
3) Heating ΔT due to dielectric losses as function of the frequency (f) and amplitude (V) of the sinusoidal signal applied to the piezostacks,
4) Transient response of the actuator to a steep variation ΔF of the preloading force F.

Experimental results and discussion

Repeatability test at T=4.4K

The sensitivity of a PICMA type piezostacks to a preloading axial force at cryogenic temperature was investigated. The variations of the relative capacitance $\Delta Cp = Cp - Cp_0$, with reference to the capacitance Cp_0 of the actuator when it is subjected to the arm preload $F_0 = 733$ N, as function of the preloading force F at T= 4.2 K are shown in Fig. 8. In order to measure the repeatability of the experimental data, two runs were performed for F increasing from 0 up to 4 kN.
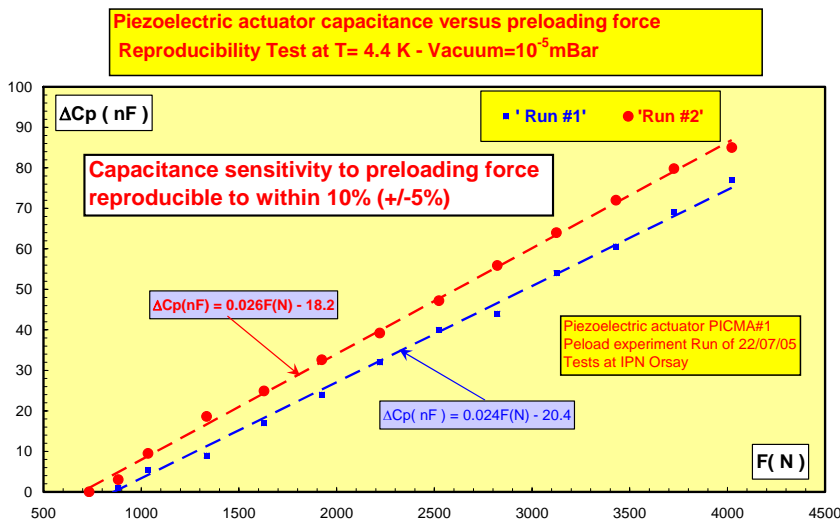

Fig. 8: Sensitivity to preloading at T=4.4 K (Reproducibility test), Cp_0=3.134 μF.

The data show a linear behavior of ΔCp vs. F. Moreover, we observe a good repeatability of $\pm 5\%$ for the slope $\Delta Cp/\Delta F = 25nF/kN$ at T=4.4K for F increasing from 0 to 4 kN.

Sensitivity to preloading at T=2.05K

The sensitivity of the actuator to preloading was measured at T=2.05 (T=2 K: ILC operating temperature) for increasing and decreasing load (Fig. 9). Non linear effects are observed at low preloading force when F is increased from zero: they are due to friction, stick-slip among non linear phenomena in the preloading device mechanism (rotating arm, bellows,…). Further, these data clearly show a large hysteresis for increasing and decreasing the preloading force. This behavior could be attributed to the intrinsic irreversibilities in the piezoelectric material itself.
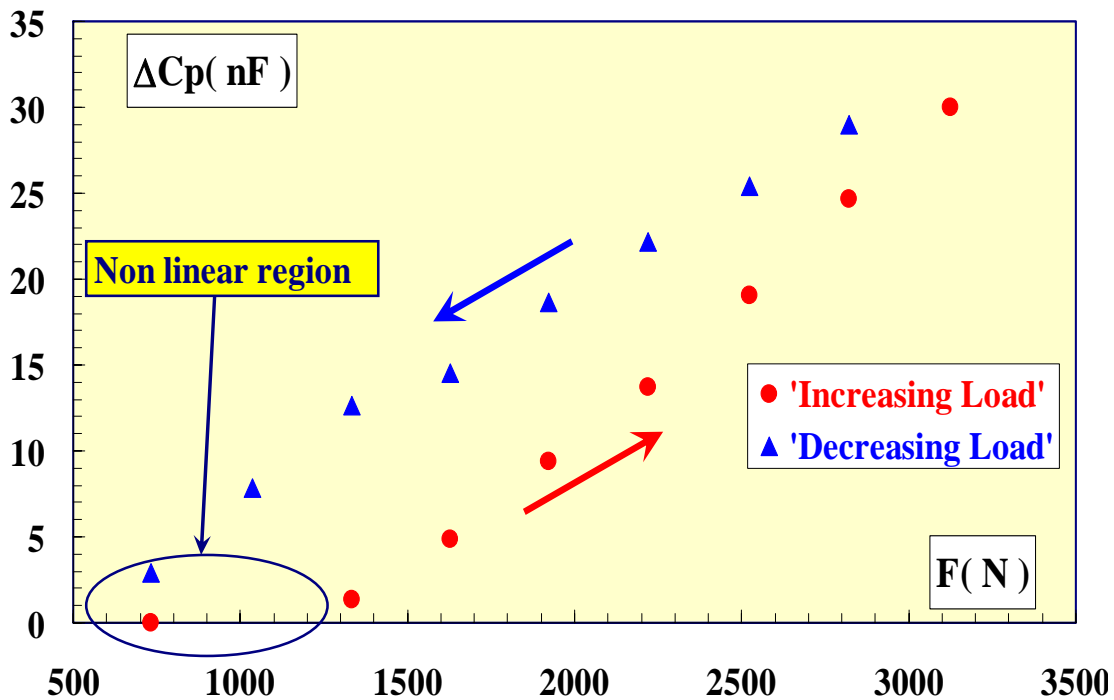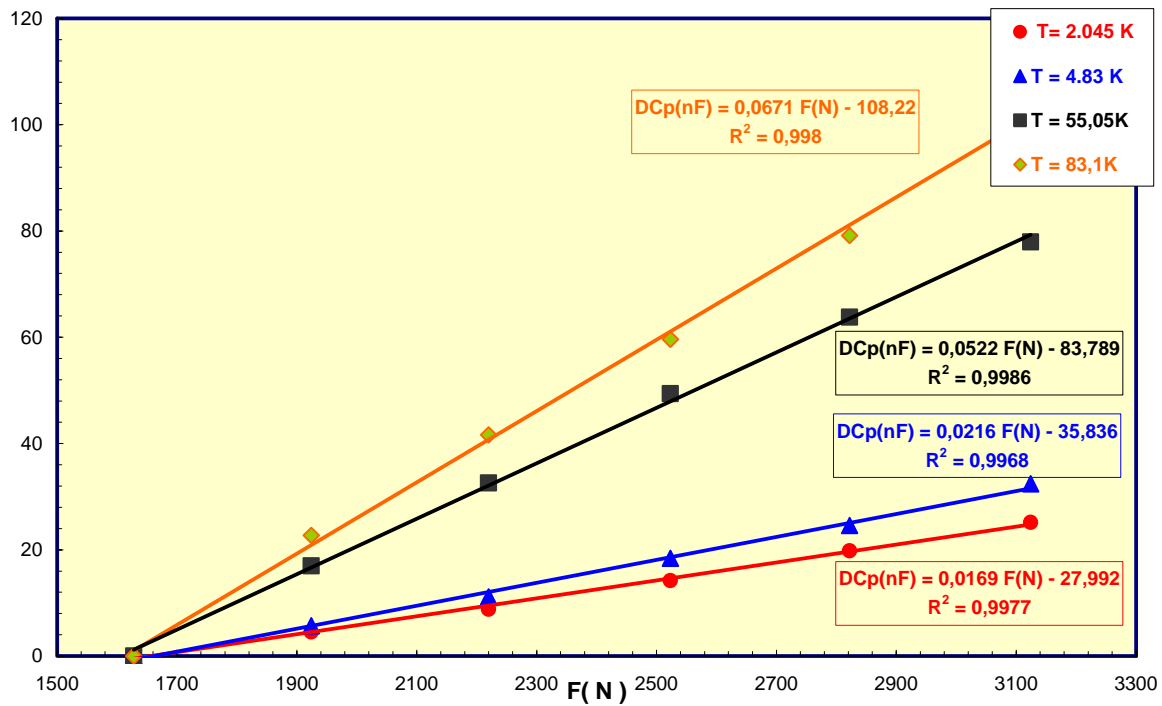

Fig. 9: Capacitance versus preload at T=2.05 K), Cp_0=2.879 µF.

At T= 2.05K, the measured sensitivity to preloading are 16nF/kN (respectively 10nF/kN) for F increasing (respectively decreasing).
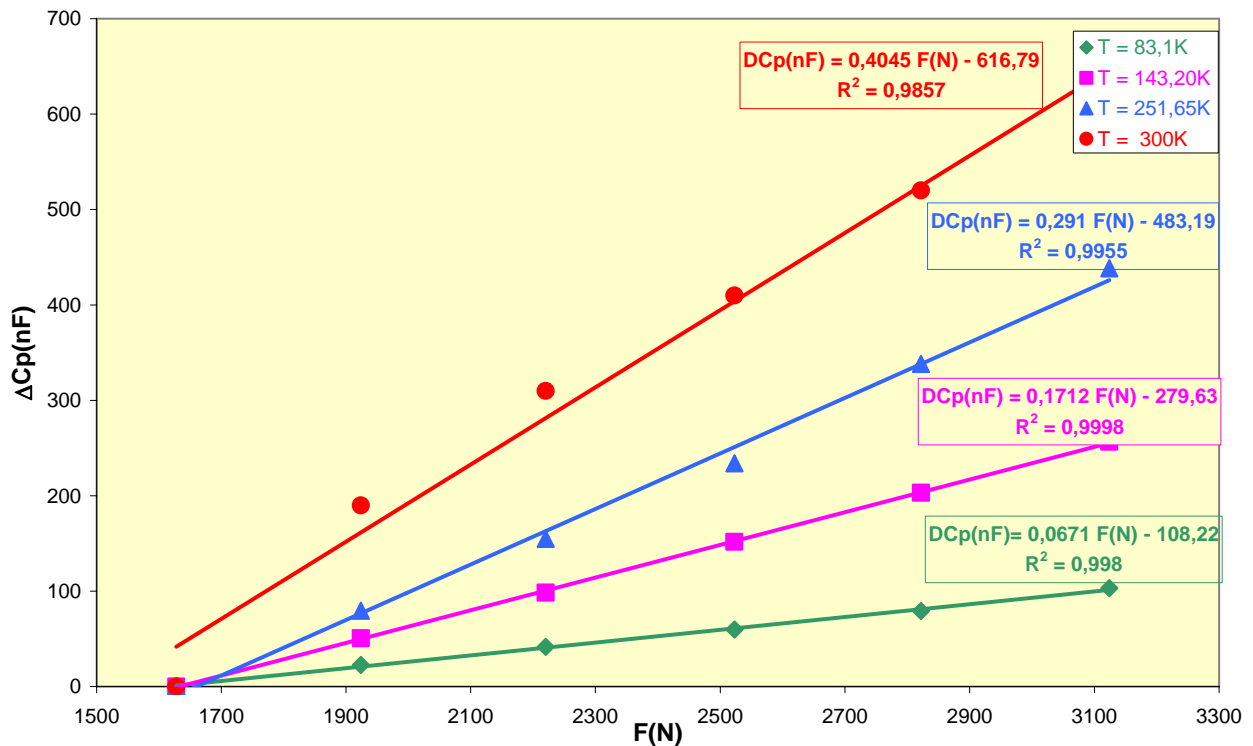
Effect of temperature on the sensitivity to preloading

We investigate the effect of the actuator temperature on its sensitivity to preloading. Systematic measurements of ΔCp vs. F were performed for T in the range 1.7 K- 300K. The corresponding data are presented in Fig. 10- Fig. 11.

Fig. 10: Capacitance versus preload for T in the range 2.05 K-83K

These results clearly show a linear dependence of the capacitance variation with the applied preload in the whole temperature range. Further, the non linear effects observed at T= 2K and low preloading force, are confirmed for all temperatures.

Fig. 11: Capacitance versus preload for T in the range 83K -300K

Moreover the sensitivity to preloading (linear region) depends strongly on the temperature as illustrated in Fig. 12: these data are simply the slopes of the previous ΔCp vs. F curves.
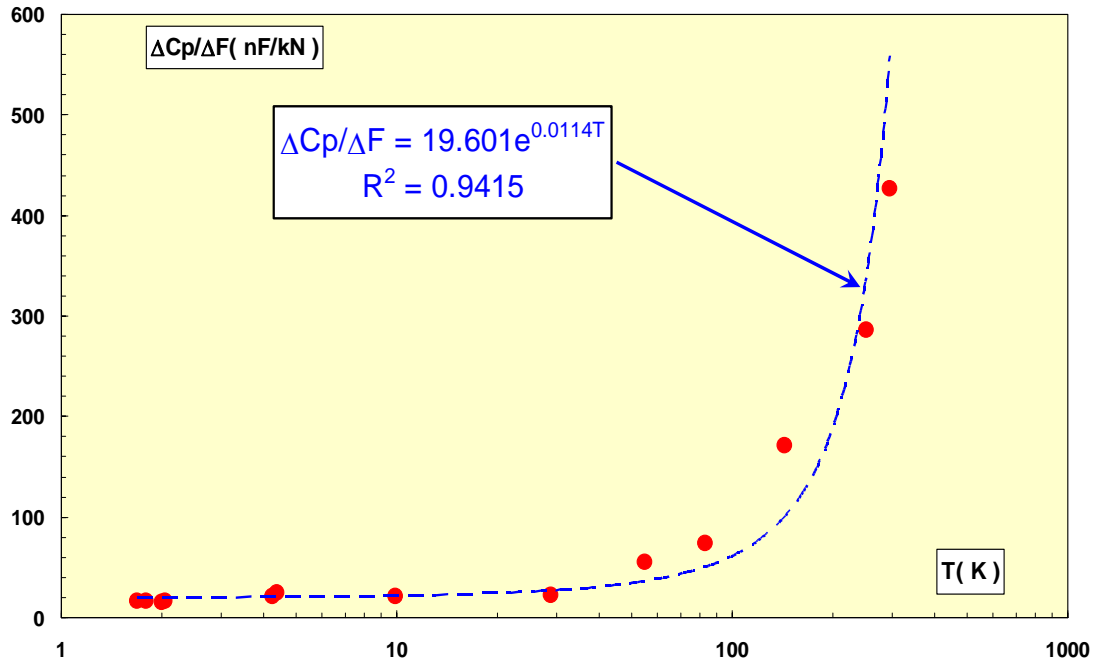

Fig. 12: Sensitivity to preloading versus temperature

More precisely, $\Delta Cp/\Delta F$ show exponential dependence on T: $\Delta Cp/\Delta F$ increases with T from 16 nF/kN at T=2 K to 426 nF/kN at T=300 K (increasing preload).

Piezostacks as dynamic force sensor

The behavior of the piezostacks as dynamic force sensor was also studied. The transient response of a PICMA type actuator to a steep preload variation ΔF=150 N at T=2K is presented in Fig. 13. The results call for the following remarks: 1) a steep voltage increase (capacitor charging) followed by an exponential decrease (capacitor discharging) is observed, 2) the peak actuator voltage ΔV_p is repeatable (3 %).
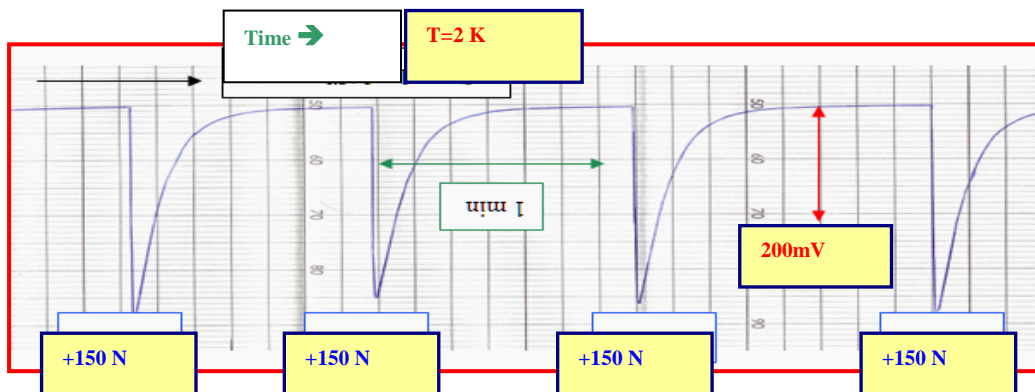

Fig. 13: Transient response of a PICMA type actuator to a steep preload variation ΔF=150 N at T= 2 K.

The transient response of the actuator to various negative and positive steep preloads variations $\Delta F=\pm n \times 150$ N (n=1, 2, 3) was recorded (Fig.14) at T=4.2 K.
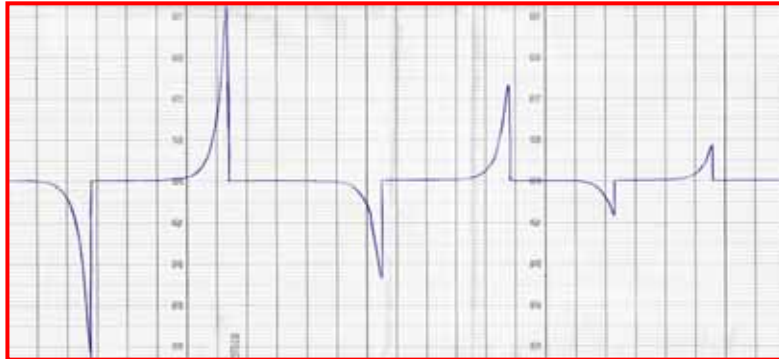

Fig. 14: Transient response of a PICMA type actuator to various steep preload variation $\Delta F=\pm n \times 150$ N (n=1, 2, 3) at T=4.2 K.

The data of Fig. 14 show the reversibility and the linearity of the response: the peak voltage is proportional to preload variation ($\Delta V_p \propto \Delta F$) and change de sign with ΔF. This behavior is clearly illustrated in Fig. 15- Fig.16.
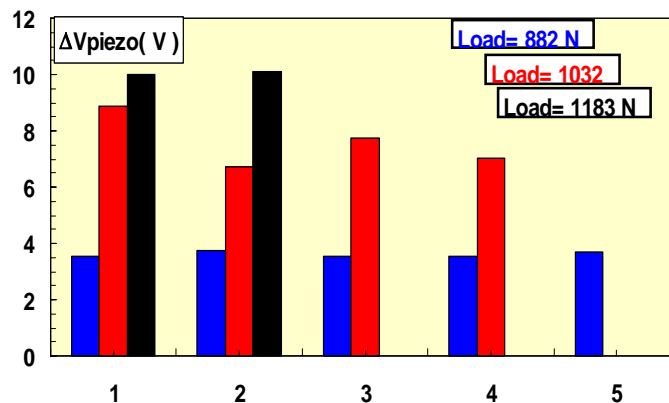
Fig. 15: Histogram of the peak voltage recorded during transient response of the actuator to various steep preload variation $\Delta F=\pm n \times 150$ N (n=1, 2, 3) at T=4.2 K.
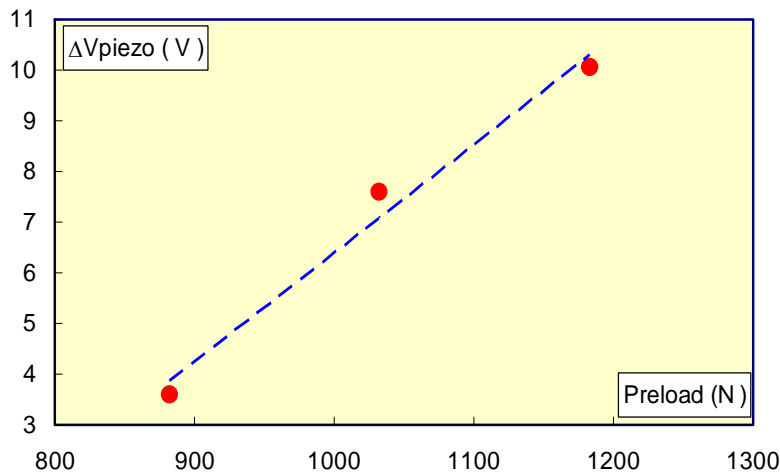
Fig. 16: Peak voltage versus preload at T=4.2 K.

The previous data lead to the following conclusions: 1) the actuator is a very sensitive dynamic force sensor with strong temperature dependence: $\Delta V_p/\Delta F=4.7V/kN$ at T=2K and $\Delta V_p/\Delta F=21.4V/kN$ at T=4.2K, 2) the response is linear ($\Delta V_p \propto \Delta F$), 3) the phenomenon is reversible with a good repeatability (3%).

Conclusion

The work presented in this report was initiated in the frame of the IPN Orsay activities within the CARE project WP#8 devoted to the development of Fast Active Cold Tuning System (FACTS). The FACTS will be used for the control and stabilization of SRF cavities frequency (cavity tuning at cryogenic temperature, dynamic compensation of Lorentz detuning and damping of micro-phonics). In this context, we designed and constructed an apparatus dedicated to the study of the electromechanical and dynamic behavior of prototype piezoelectric actuator subjected to variable preloading force at cryogenic temperatures. The preloading of piezostacks actuators is mandatory in order to increase their lifetime. The preloading apparatus was successfully used for testing a PICMA type piezoelectric actuator for temperature T in the range 2K-300K and preloading force F ranging from 733N to 4kN. In the whole temperature range, the actuator capacitance Cp increases linearly with F. The sensitivity of the actuator to preloading $\Delta Cp/\Delta F$ shows exponential dependence on T: $\Delta Cp/\Delta F$ increases with T from 16 nF/kN at T=2 K to 426 nF/kN at T=300 K (increasing preload). Notice that Cp vs. F curve shows a large hysteresis which seems to be intrinsic to the material of the actuator. The behavior of the piezostacks as dynamic force sensor was also studied at T=2 K and T=4.2K. The experimental data show the reversibility and good repeatability (3%). These data lead to several observations: a) the response is linear namely the peak voltage is proportional to preload variation ($\Delta V_p \propto \Delta F$) and change de sign with ΔF, b) the actuator is a very sensitive dynamic force sensor with strong temperature dependence: $\Delta V_p/\Delta F=4.7V/kN$ at T=2K and $\Delta V_p/\Delta F=21.4V/kN$ at T=4.2K. These calibration data were used successfully for measuring the variations of the force applied to the actuator by the tuning system in operation on C45 cavity [12]. The corresponding results will be presented in a next report.

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