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

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Abstract

In the frame of the CARE project activities supported by EU, IPN Orsay participates to the development of a fast cold tuning system for SRF cavities operating at a temperature T=2 K. The study is aimed at full characterization of piezoelectric actuators at low temperature. A new experimental facility was developed for testing various prototypes piezoelectric actuators and successfully operated for T in the range 1.8 K-300 K. Different parameters were investigated as function of T: piezoelectric actuator displacement vs. applied voltage V, capacitance vs. T, dielectric and thermal properties vs. T and finally heating ΔT due to dielectric losses vs. modulating voltage V_{mod} and frequency f. We observed a decrease of the Full Range Displacement (FRD or ΔX) of the actuators from ~40µm @ 300K down to 1.8µm-3µm @ 1.8K, depending on both material and fabrication process of the piezostacks. Besides, both material and fabrication process have a strong influence on the shape of the characteristics ΔX vs. T dependence. Moreover, the variations of loss tangent ($tg(\delta)$) with T show a maximum at T in the range 30 K-120 K. Finally a dedicated facility located at Orléans (CERI) for radiation hardness tests of actuators with fast neutrons at T=4.2 K was developed and the first beam tests results are summarized.

INTRODUCTION

Superconducting RF (SRF) cavities are very sensitive to small mechanical perturbations due to their narrow bandwidth $\Delta f_{1/2}$. More precisely, high electromagnetic fields induce mechanical deformations (~µm) of the cavity wall, leading to a frequency detuning $\Delta f \approx \Delta f_{1/2}$
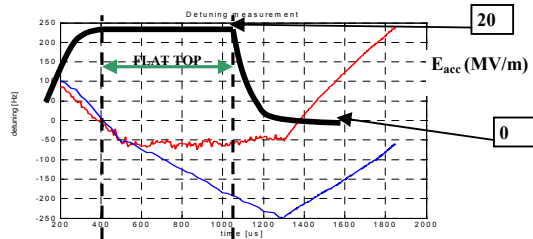

Figure 1: Compensation of Lorentz detuning by a piezoelectric actuator in a TESLA cavity for a flat top gradient E_{acc}=20MV/m (black curve): With compensation (red curve) Δf~-60Hz during flat top. b) Without compensation (blue curve), Δf~-250Hz .

of these accelerating structures (Fig.1). In order to reduce this effect, which results other ways in a substantial additional RF power so as to control E_{acc}, the SRF cavities are stiffened. However, the detuning factor K_L reached with stiffened SRF cavities (e.g Δf=- K_L. E_{acc}^2, $K_L \approx$1-2Hz/(MV/m)^2) is still much higher than needed. An alternative strategy or dynamic compensation of Lorentz force detuning, using commercial piezoelectric actuators as active elements for deforming the resonator was successfully applied (Fig.1) to TESLA cavities [1]. At last, a piezo-tuning system is actually developed at IPN Orsay for high intensity proton linacs SRF cavities. In this paper, we will report the experimental results on the characterization of piezoelectric capacitive actuators at low temperature (i.e 1.8 K-300K), we obtained recently.

EXPERIMENTAL SET UP AND TEST PROCEDURE

A dedicated facility was designed and successfully used for this purpose: the experimental details, measurements method and the first results were presented previously [2]. The actuators tested, are PZT (Lead Zirconate Titanate) piezostacks from different companies. The 3D drawing of the test-cell (Fig. 2) fulfills the following main requirements:
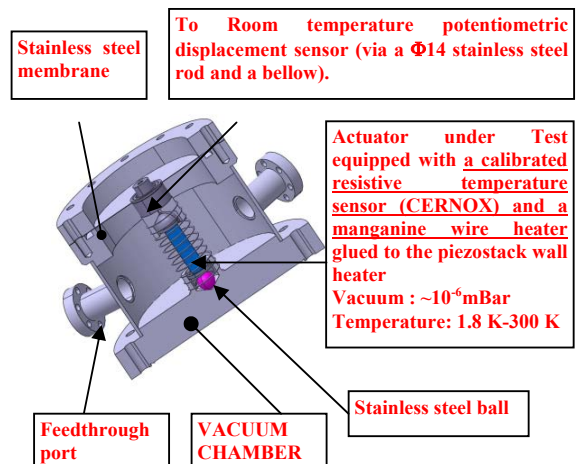

Figure 2: 3D drawing of the test-cell (See [2] for details).

-calibration and full characterization of piezoelectric actuator under vacuum and at controlled low temperature,
-to avoid any shear forces, tilting and/or torsional forces which would damage the piezostacks actuator.

The facility, which was upgraded as compared to the first version [2], operates in temperature range 1.8K–300K and allows automatic measurements of the actuators properties. More precisely, we measured the following parameters at different temperatures T: a) displacement versus voltage characteristics, b) actuator capacitance Cp vs. T, c) dielectric properties (dielectric constant: ε_r, and loss tangent: $tg(\delta)$, as function of T), d) heating ΔT due to dielectric losses as function of the frequency f and amplitude V_{mod} of the sinusoidal signal applied to the actuator, e) thermal properties (time constant: τ, thermal resistance: R_{th} and specific heat: C_{th}).

RESULTS AND DISCUSSION

Several low voltage actuators (Fig. 3) from different companies (JENA, NOLIAC, PICMA from PI) were tested.
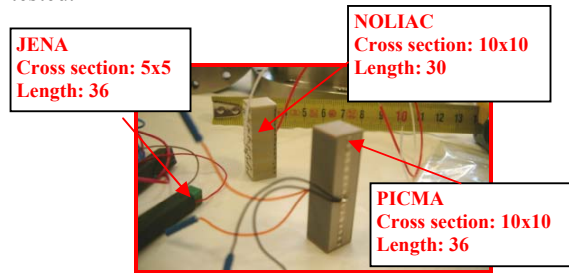

Figure 3: Piezoelectric actuators (Dimensions in mm).

Piezosystem JENA actuators results

Actuators of different production series from piezosystem JENA were investigated [2]. These actuators, which are of the same type (FRD ≈42 µm @ T=300 K (calibration curve given by JENA)), were rejected because of five main drawbacks and limitations:

1) Maximum stroke less than 2 µm at 2K (3 µm are required),
2) Insufficient blocking force : ~1kN @ 300K (3kN are required),
3) Low mechanical stiffness: 25N/µm (100 N/µm are required),
4) Lack of fabrication reproducibility from batch to batch (i.e. different behaviour of FRD vs. T),
5) Very short lifetime when operated at 2 K (electrical breakdown and/or mechanical damages).

The experimental data previously reported (JENA #9221[2]) show that the FRD of the actuator decreases strongly with T from 42 µm @ 300 K down to 2 µm @ 2K. For this actuators, the measured variations of $tg(\delta)$ at 100Hz as function of T show a peak around T~10K-20K. As a consequence, when the actuator is subjected to a sine voltage, the dielectric losses P_{diel} versus T curve shows also a broad maximum around T ~10K-20K. For a sinusoidal displacement of 1µm amplitude at a frequency of 100 Hz, the thermal load to 1.8K is lower than 1 mW.

PICMA actuators results

These prototypes actuators from PI are not calibrated. We used JENA actuators and the displacement sensor for the calibration of PICMA (Fig. 5) and NOLIAC actuators. These data show the well known hysteresis @ 300K with a FRD of 40 µm @ V_{max}=120V. Note that this hysteresis is completely negligible for T< 4.2 K.
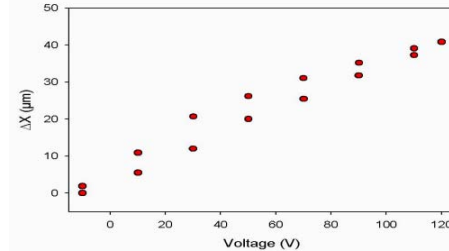

Figure 5: Calibration of actuator PICMA#1@ 300 K.

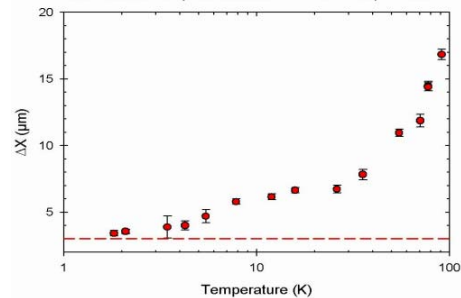The variations of the maximum actuator PICMA#1 expansion ΔX with temperature are shown in Fig. 6.

Figure 6: Variations of the full range (V_{max}=120 V) displacement with temperature (Actuator: PICMA#1).

These data show a strong decrease of the slope of ΔX vs. T curve with temperature. This behavior seems to be mainly due to the strong dependence (Fig. 7) of the actuator PICMA#1 parallel capacitance Cp on T. Note that FRD is decreased by a factor of ~13 when T decreases from 300 K down to 2 K and this result is in the range of values reported previously by other authors [3].

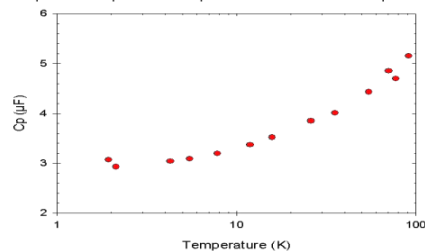Fig. 7: Actuator capacitance versus temperature.

Moreover, at low temperature (i.e T≤100 K), we notice (Fig. 8) a simple relationship between ΔX and C_p (i.e; $\Delta X \propto C_p$). This behavior gives a straight-forward mean to calibrate actuators. Indeed, capacitance measurements are more simple and less time consuming, as compared to a true calibration (i.e. ΔX vs. T) and specially for a large number of actuators (e.g. ~1000 for the XFEL).
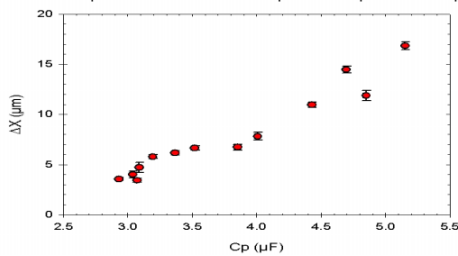
Figure 8: Full range displacement versus capacitance.

Dielectric and thermal properties

Measurements of the following parameters were performed for T ranging from 1.8K to 300K: a) dielectric properties (i.e. Cp, tg(δ) @ 100Hz, 120 Hz and 1kHz), heating ΔT vs. sinusoidal voltage amplitude V_{mod} and frequency f, b) thermal properties (C_{th}, R_{th} and τ).

The dielectric constant ε_r of the material vs. T, which is deduced from Cp, is obviously homothetic to the curve of Fig.7: ε_r decreases from 1454 @300K to 328 @1.8K. The heating ΔT versus time when the actuator is subjected to a sinusoidal voltage (T=1.8K) is shown in Fig. 9.
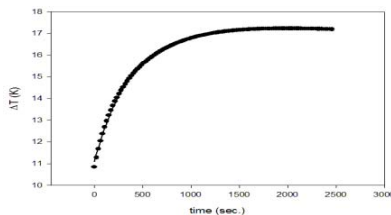

Fig. 9: Dielectric heating ΔT of the actuator @ T=1.8 K (sinusoidal voltage : V_{mod}=1.5 V, f=100 Hz).

These data clearly show an exponential dependence on the time t: ΔT= $\Delta T_{max}.(1-exp(-t/\tau))$, where the time constant τ is simply given by τ= $R_{th} C_{th}$. The fit to the data leads to the following values: τ=376 s, R_{th}=9.10^{5}mK/mW and C_{th}=4.310^{-4} J/K. Note that V_{mod} corresponds to a displacement of 170 nm of the cavity wall (i.e. Δf=68 Hz) with total dielectric losses P_{diel}= 20 μW and heating ΔT=17K (steady state value: see Fig. 9). Moreover, the heating ΔT vs. modulation voltage amplitude and frequency is shown in 3D plot (Fig. 10). The observed heating (i.e. $\Delta T=R_{th}.P_{diel}$) is well described by the well-known expression of the total dielectric losses P_{diel} (i.e. $\Delta T\propto$ P_{diel} =$\pi.f.Cp.V_{mod}^2.sin(\delta)$). Note that the small departure from the quadratic dependence (1), observed at high modulation voltage amplitude and or frequency, is attributed to nonlinear effect resulting from Cp and sin(δ) dependence on T.

CONCLUSION AND OUTLOOK

A dedicated apparatus was developed for full characterization of piezoelectric actuators at low temperature 1.8 K-300 K. Several PZT actuators from three different companies were fully characterized; ΔX
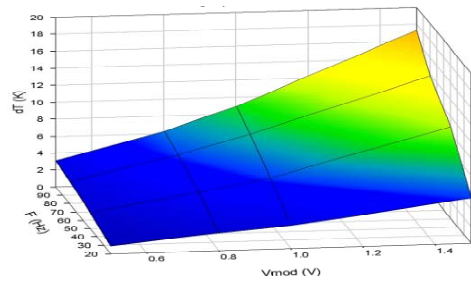

Figure 10: 3D plot o vs. heating modulation voltage amplitude and frequency.

ΔX decreases strongly with T from ~40 μm @ T=300 K down to 1.8 μm -3 μm @ T=1.8 K. The shape of ΔX vs. T curve depends on the actuator material and fabrication process. For actuators of PICMA and NOLIAC type, ΔX=2.8μm-3μm @1.8K leading to a theoretical detuning compensation $\Delta f\approx$1kHz for TESLA nine cells cavities. The dielectric losses of JENA actuators, for a sinusoidal (@f=100 Hz) displacement of 1 μm amplitude at 1.8 K, are lower than 1mW. Furthermore, four PICMA and four NOLIAC actuators were subjected to irradiation tests (CERI institute) at T=4.2 K with a fast neutrons beam (Energy spectrum: 1-15MeV). A total dose of ~2.10^{15}n/cm^2 was achieved in 16 hours: neither damage nor anomalous behavior or performance degradation of these actuators were observed. Only C_p increase, which are probably due to a thermal effect (i.e. heating with neutrons) were observed. A detailed report on irradiation will be published when data analysis is completed. A new apparatus for investigating the dynamic properties of actuators, effect of preloading on their characteristics is under development. Finally, the actuators will be integrated in a cold tuning system for TESLA cavities and tests will be performed soon in the horizontal cryostat facilities CRYHOLAB at Saclay and CHECHIA at Desy.

REFERENCES

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