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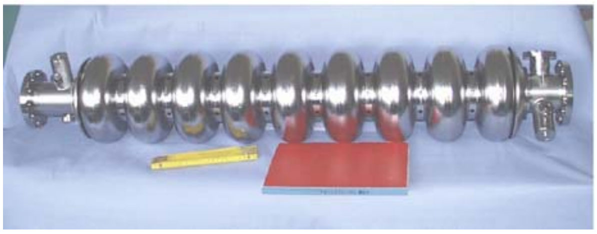
SRF



LOW TEMPERATURE ELECTROMECHANICAL AND DYNAMIC PROPERTIES OF PIEZOSTACKS FOR SUPERCONDUCTING RF CAVITIES FAST TUNERS

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Abstract

Piezoelectric actuators are integrated as active element in Fast Cold Tuning Systems and used to compensate dynamically the frequency shift induced by high surface magnetic fields in Superconducting RF cavities. In the frame of the European CARE project, we designed and constructed three apparatus dedicated to the measurements of electromechanical (capacitance, loss factor, displacement), thermal (specific heat, interfacial thermal resistance) and dynamic properties (effect of a preloading force) of piezostacks for T in the range 2K-300K. Moreover, radiations hardness tests were also performed with fast neutrons beams at T=4.2K. The experimental data we obtained are analyzed and discussed.

Contribution to the EPAC’06, Edinburgh, UK

Work supported by the European Community-Research Infrastructure Activity under the FP6 “Structuring the European Research Area” programme (CARE, contract number RII3-CT-2003-506395)

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INTRODUCTION

Due to their narrow bandwidth Δf_{BW}, Superconducting RF (SRF) cavities are very sensitive to small mechanical perturbations which change the volume of the resonator. More precisely, high electromagnetic fields (e.g., radiation pressure) induce mechanical deformations (~µm) of the thin (~3mm-4mm) cavity wall, resulting in a frequency shift or Lorentz detuning $\Delta f_L \approx \Delta f_{BW}$ of these accelerating structures. Moreover, the radiation pressure P depends quadratically on the surface RF electric (E_S) and magnetic (H_S) fields according to the relationship $P = \frac{1}{4}\cdot(\mu_0 H_S^2 - \varepsilon_0 E_S^2)$. The radiation pressure P ~ kN/m^2 for TESLA cavities at an accelerating field E_{acc}=25MV/m. By using Slater formulae (e.g., $\frac{\Delta f_L}{f_O} = \frac{1}{4W}\cdot\iiint_{\Delta V} P\cdot dV$) where ΔV is the change of the resonator volume due to radiation pressure and f_0 is the fundamental mode frequency, the Lorentz detuning Δf_L is computed by numerical codes. This leads to the expression $\Delta f_L = -K_L.E_{acc}^2$, where the detuning factor K_L is a parameter depending on the cavity material, its shape and the boundary conditions. An additional RF power is then needed to operate the cavity if this detuning is not compensated. The ratio of the RF power P_{RF} to that needed in the ideal case P_{RF0} (e.g., zero detuning) is given by the expression: $\frac{P_{RF}}{P_{RF0}} = 1 + \alpha.\left(\frac{\Delta f(t)}{\Delta f_{BW}}\right)^2$, where α is a constant depending on the matching conditions: α =0.25 with beam, α =1 without the beam. The measured detuning factor for TESLA cavities in pulsed mode operation (ILC machine, pulse duration: 1.3 ms, repetition rate: 5Hz, E_{acc}=33MV/m for a centre of mass energy E_{cm}=800GeV) is $K_L \cong 0.5\text{-}1$ Hz/(MV/m^2)

leading to a maximum frequency shift Δf_L=1090 Hz at E_{acc}=33MV/m. Moreover, the cavity bandwidth is Δf_{BW}=425 Hz. The RF power needed is then increased by a factor 2.64 W as compared to non detuned cavity. It is then mandatory to compensate this detuning in order to save power. A dynamic compensation of Lorentz detuning, using commercial piezoelectric actuators as active elements for deforming the resonator was successfully applied (Fig. 1) to TESLA cavities [1].

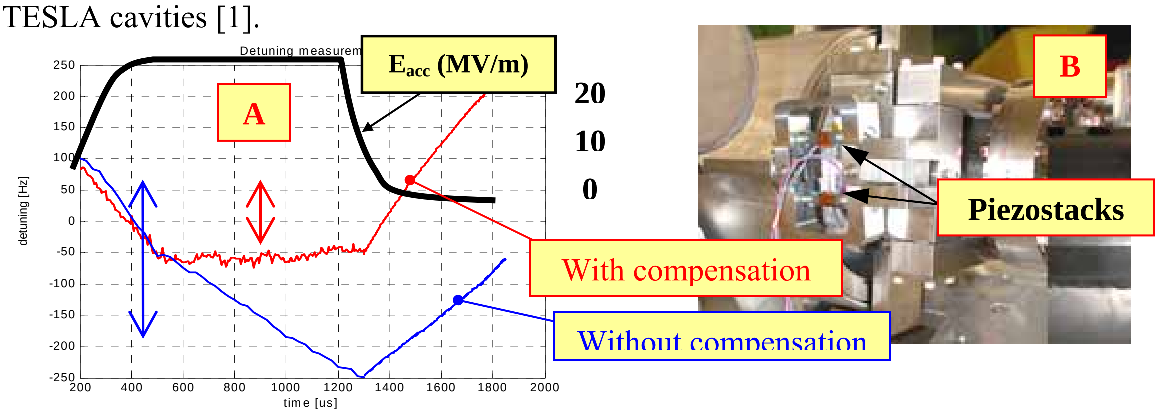

Figure 1 Compensation of detuning by a piezoelectric actuator in a TESLA cavity for a flat top gradient E_{acc}=20MV/m (black curve) (A). Actuators attached to the tuning system (B).

The measured detuning with and without compensation are respectively Δf_L~-60Hz and Δf_L~-250Hz. Further, during the flat top of E_{acc} (Beam on) Δf_L ~-10 Hz (with compensation) and ~-200Hz (without compensation). Due to the lack of data for the operating conditions of the piezoelectric actuators in the cryomodule and accelerator environment (vacuum: 10^{-5} mbar, cryogenic temperatures, radiation), an experimental program aiming at full characterization of piezoelectric actuators at low temperature (i.e., 1.8 K-300K) was launched in the frame of the CARE project. In this paper, we will report the experimental results, we obtained recently.

EXPERIMENTAL RESULTS AND DISCUSSION

Several dedicated facilities were developed for this purpose: the experimental details, measurements method were described previously [2-3]. The diagram of test-cell and photographs of the piezostacks tested (PZT: Lead Zirconate Titanate) are shown in figure 2.

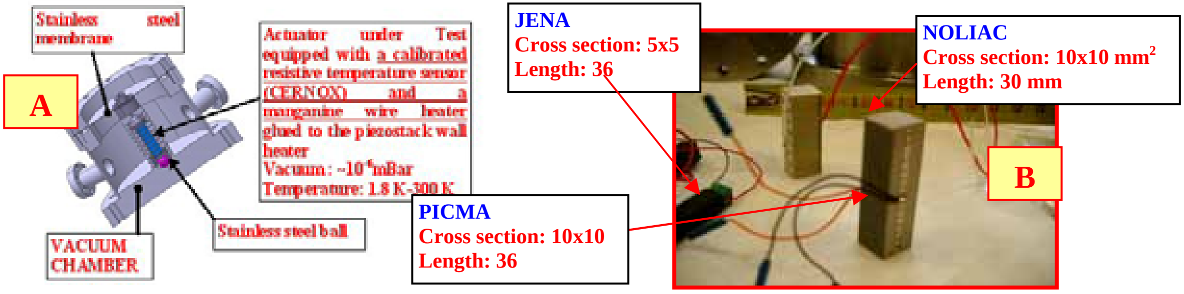

Figure 2 Diagram of the test cell (A), Photograph of piezostacks tested (B)

These facilities operate in temperature range 1.8K– 300K and allow automatic measurements of the following properties as function of T: a) displacement versus voltage characteristics, b) dielectric properties (capacitance: Cp, loss factor: tg(δ), impedance), c) heating ΔT due to dielectric losses when the actuator is subjected to a sinusoidal voltage, d)thermal properties (time constant: τ, thermal resistance: R_{th} and thermal capacitance: C_{th}). The results are presented in figure 3. These data show a strong monotonic decrease of the capacitance with the temperature. In contrast the shape of tg(δ) vs. T curves of Picma and Noliac actuators are quite different. However, they exhibit a maximum respectively at T≈20K (Noliac) and T≈90K (Picma). This feature (e.g., peak in tg(δ) vs. T curve) was also observed with actuators from Jena and is common to PZT piezostacks. The exact shape seems tightly linked to the piezoelectric material (chemical composition, grain size) and the fabrication process which depends on the supplier.

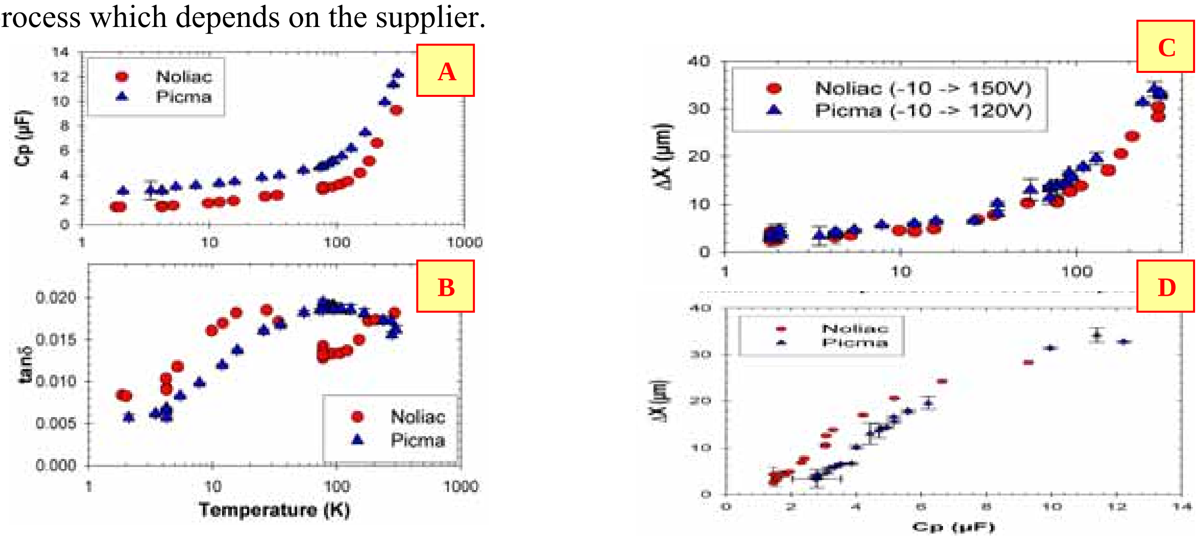

Figure 3 Capacitance vs. T (A), Loss factor vs. T (B), Displacement vs. T (C), Displacement vs. Capacitance (D).

Moreover, the maximum displacement ΔX decreases strongly with T. This non linear behaviour was previously observed by other groups [4]: depending on the piezostacks material ΔX is decreased by a factor 5 to 20 when T is lowered from 300 K down to T=4 K. Finally, it should be stressed that ΔX vs. T and C_p vs. T curves are homothetic. Obviously C_p and ΔX are tightly correlated as illustrated in figure 3D (Picma piezostacks data) thus confirming our observation with Jena piezostacks [2]. This is an important feature, which gives a simple mean for indirect calibration (e.g., ΔX vs. T) of a large number (i.e., ~2000 actuators needed for XFEL, ~40000 actuators for ILC) of piezostacks: capacitance measurement are easier and less time consuming as compared to true calibration (e.g., Displacement vs. actuator voltage for different T). Further, as the actuators will operate in dynamic conditions for active tuning of SRF cavities (Lorentz detuning, damping of micro-phonics), the effect of time varying voltage was investigated. For this purpose, the actuator is subjected to a sinusoidal voltage (amplitude: V_{mod}, frequency: f_{mod}) and the heating ΔT is recorded as function of time (Fig. 4A, Picma piezostacks).

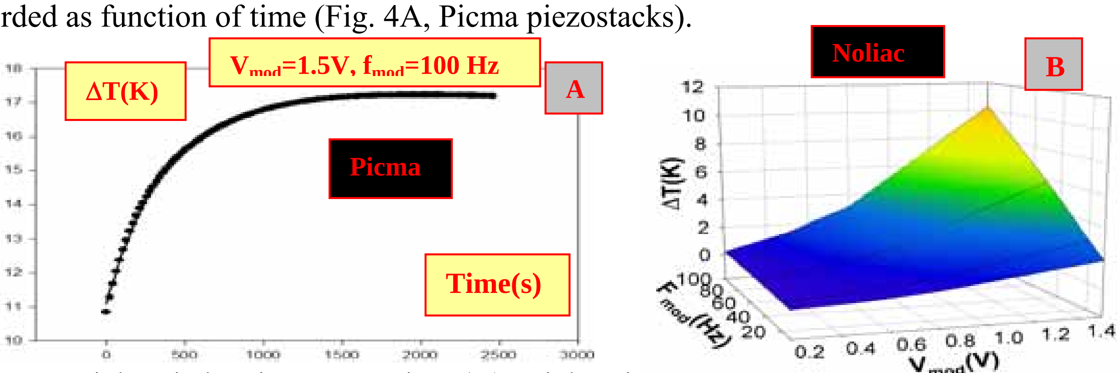

Figure 4 Dielectric heating versus time (A), Dielectric heating versus f_{mod} and V_{mod} (B)

The heating ΔT vs. time curve is exponential ($\Delta T(t)=\Delta T_{ma}x.(1-\exp(-t/\tau))$. The time constant τ is simply given by $\tau = R_{th}.C_{th}$ ($C_{th} = C_0.m$, C_0: specific heat, m: mass of piezostacks). The fit to data leads to: τ= 375.5 s, $R_{th}=9.10^5$ K/W, C_0= 20 mJ/Kg.K. Data obtained with Noliac piezostacks (Fig. 4B) show steady-state ΔT values as function of V_{mod} and f_{mod}. Obviously ΔT is proportional to the dielectric losses P_{diel} ($\Delta T=R_{th}.P_{diél}$) which are given by $P_{diel}=\pi C_p f_{mod} V_{mod}^2 \sin\delta$. The data show quadratic dependence with V_{mod} and linear dependence with f_{mod}. Finally, we investigated the effect of fast neutrons at T=4.2 K on piezoelectric actuator properties after an exposure to a dose higher than 10^{14}neutrons/cm² in ~20 hours. Experimental details and discussion of the results are given elsewhere [5]. Three beam tests were performed: four Picma actuators in test #1, four Noliac actuators in test #2 and three Jena actuators for test #3. After cool down to T=4.2K, the dielectric properties are measured without beam. Then, the actuators are subjected to fast neutrons radiation during ~20h00 and the parameters are on-line measured. Notice that due to heating by neutrons beam, some parameters (e.g., C_p) increases with beam intensity. The final dielectric properties measured after neutrons exposure, are compared to the values before radiation as illustrated in figure 5.

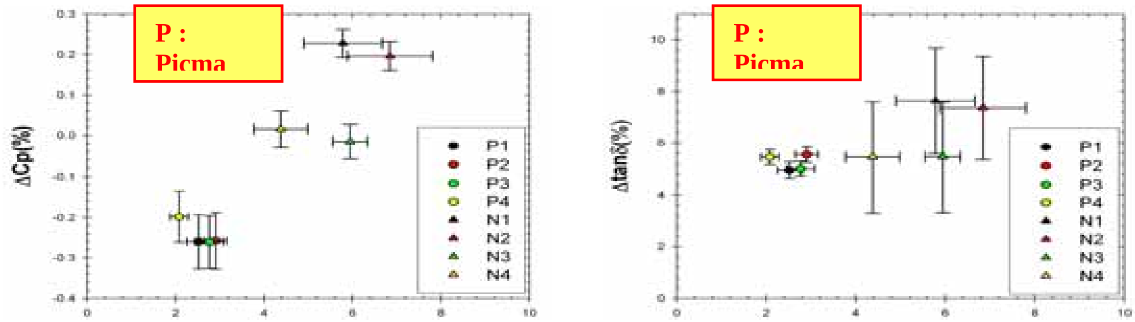

Figure 5 Effect of fast neutrons dose on capacitance (A) and loss factor at T=4.2 K

In the range of neutrons dose investigated (2- 7.10^{14} n/cm^2): a) Cp decreases by 0.25% for Picma actuators, b) Cp increases by 0.15% for Noliac actuators, c)loss factor increases by 5 to 10 %. In conclusion, no major damage was observed but slight performance degradation may be due to aging effect, is measured: these piezostacks are suited for use in cryogenic and neutrons radiation environment up to a total dose ~ 7.10^{14} n/cm^2.

ACKNOWLEDGEMENT

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