Piezo ceramics for LLRF

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INFN Milano - LASA

WHY PIEZO CERAMICS ARE NEEDED IN SUPERCONDUCTING RF SYSTEMS?

Motivation (1/3)

Why do we need a Lorentz force detuning compensation system?

The cavities are pulsed at high field.

The field generates the radiation pressure, which interacts with cavity walls.

The cavity changes its dimensions,

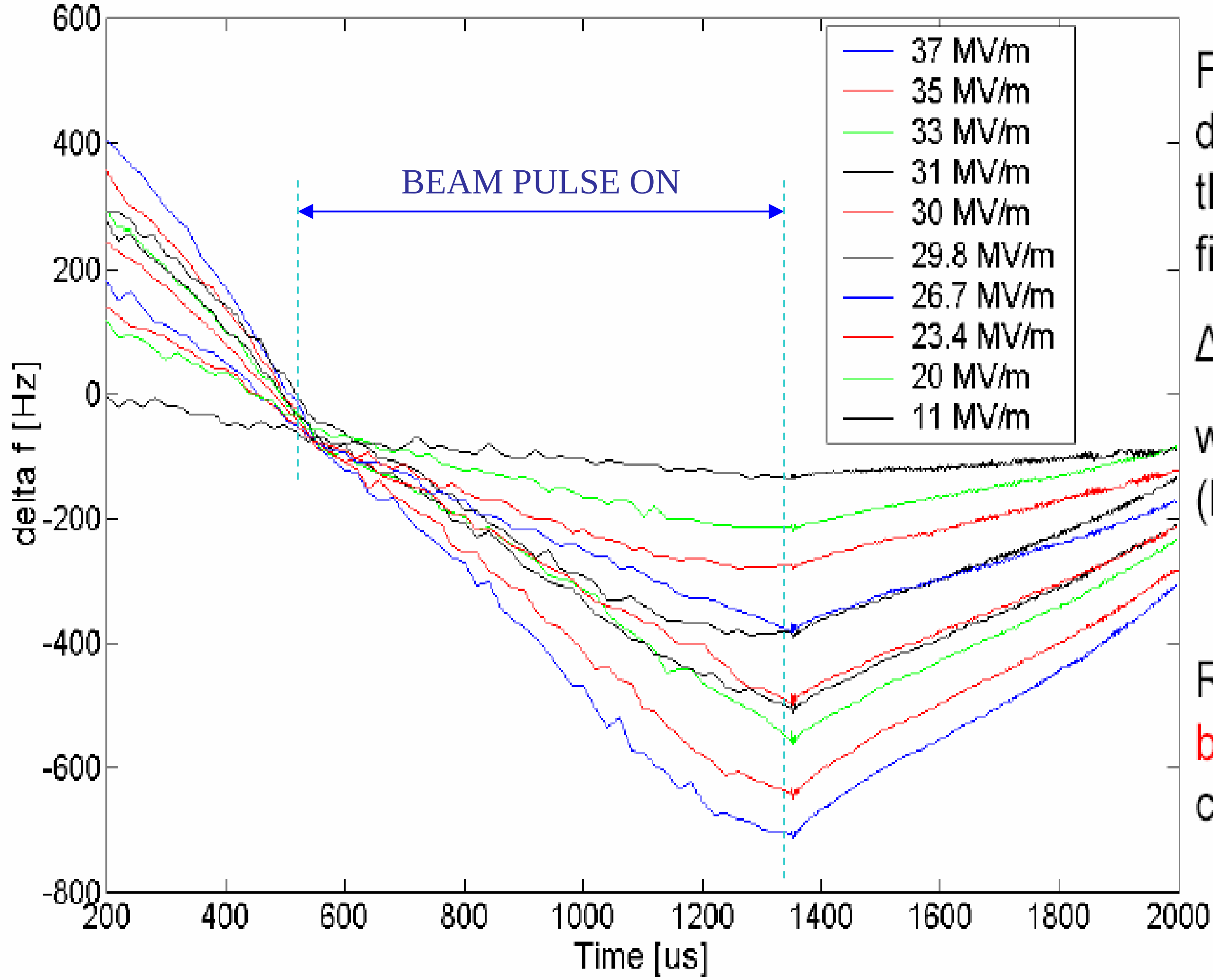
The change of the resonant frequency of the cavity,

The master oscillator frequency is constant.

De-tuned cavity

Motivation (2/3)

Why do we need a Lorentz force detuning compensation system?



Frequency detuning due Lorentz forces of the electromagnetic field in the cavities:

$\Delta f = K \cdot E_{acc}^2$

where $K \approx 1$ Hz / $(MV/m)^2$

Remember: Cavity bandwidth with main coupler is ≈ 300 Hz

Motivation (3/3)

How to maintain the constant phase and amplitude during the RF pulse ?

1. Additional RF power
   for field control could be used

2. Passive detuning system
   (stiffness rings, stiffer cavity, fixture)
   could be used

3. Active detuning system
   with piezoelectric and/or magnetostrictive
   device could be used

WP8 Main Tasks

8.1 UMI (coaxial) tuner

8.2 Magnetostrictive tuner

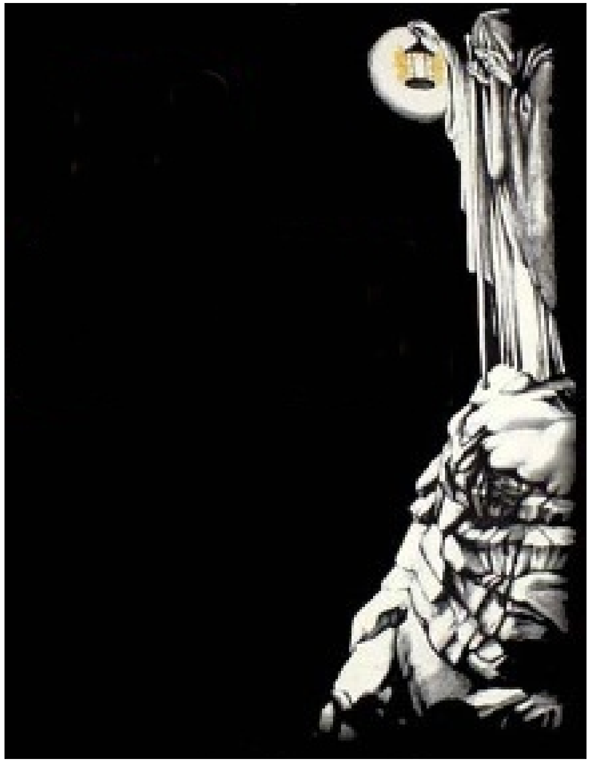
8.3 CEA tuner

8.4 Piezo characterization

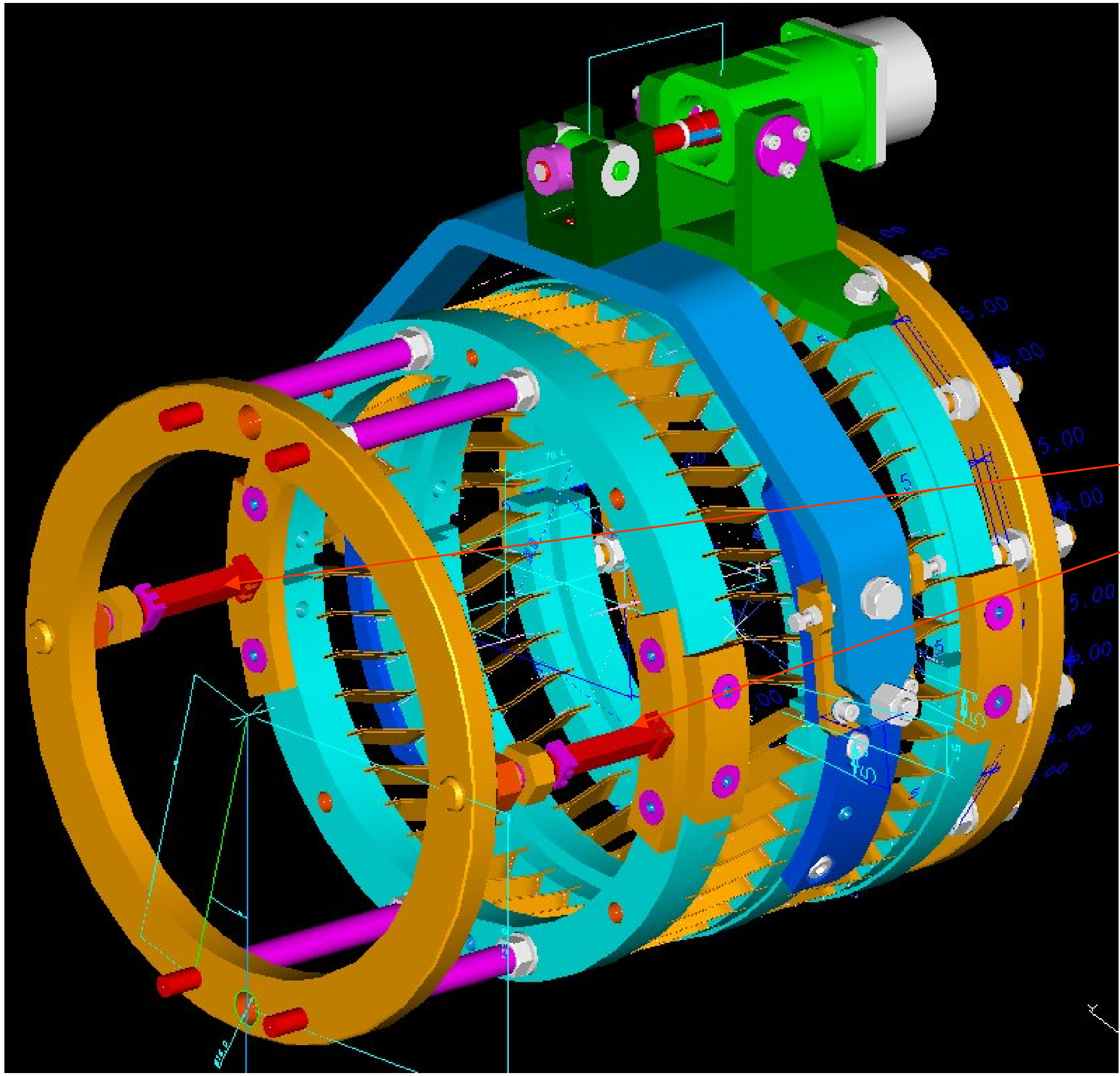
WHERE PIEZO CERAMICS ARE USED?

Examples:

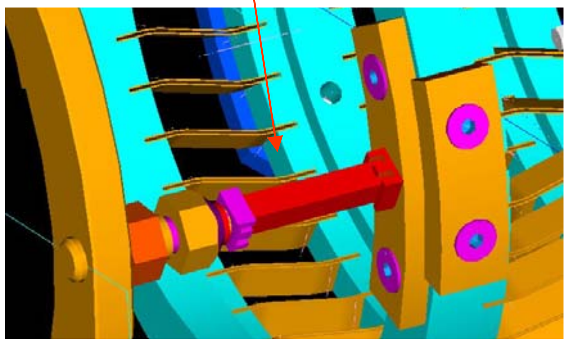
- Coaxial Blade Tuner
- CEA Tuners I & II



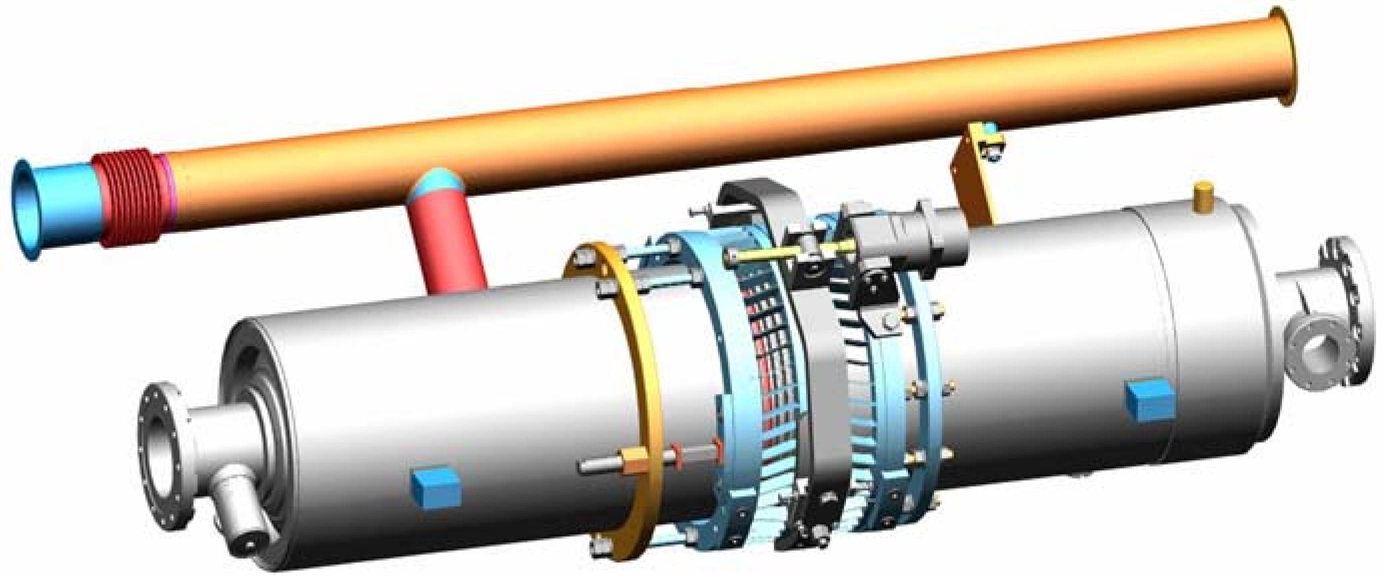
The INFN Blade-Tuner

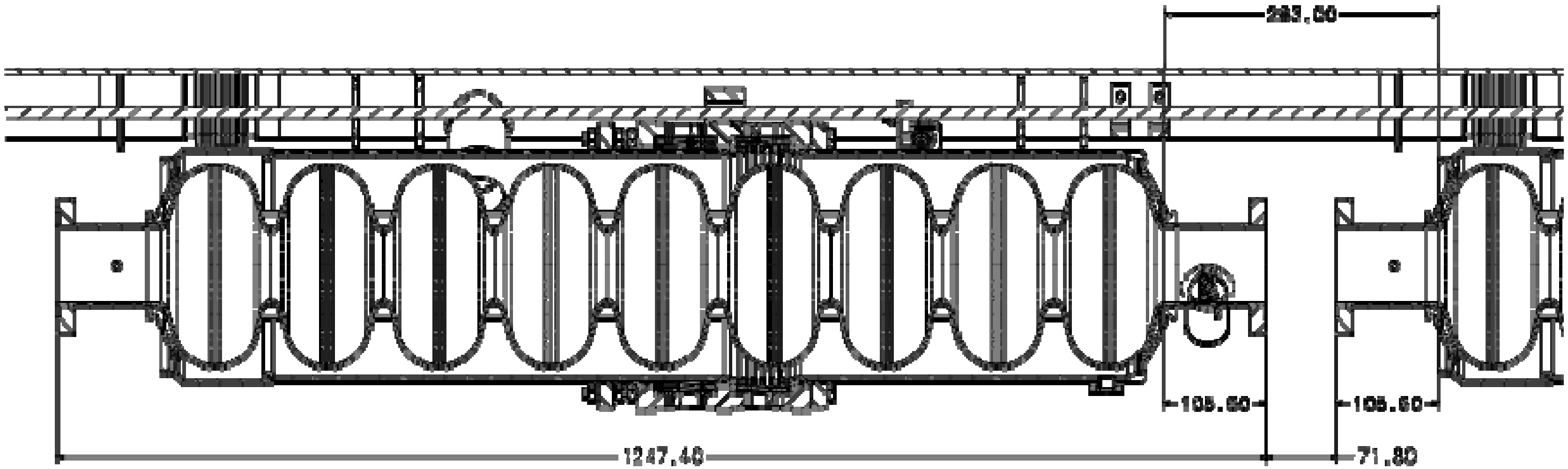


The first two prototypes are going to be tested at FNAL and DESY in horizontal cryostats



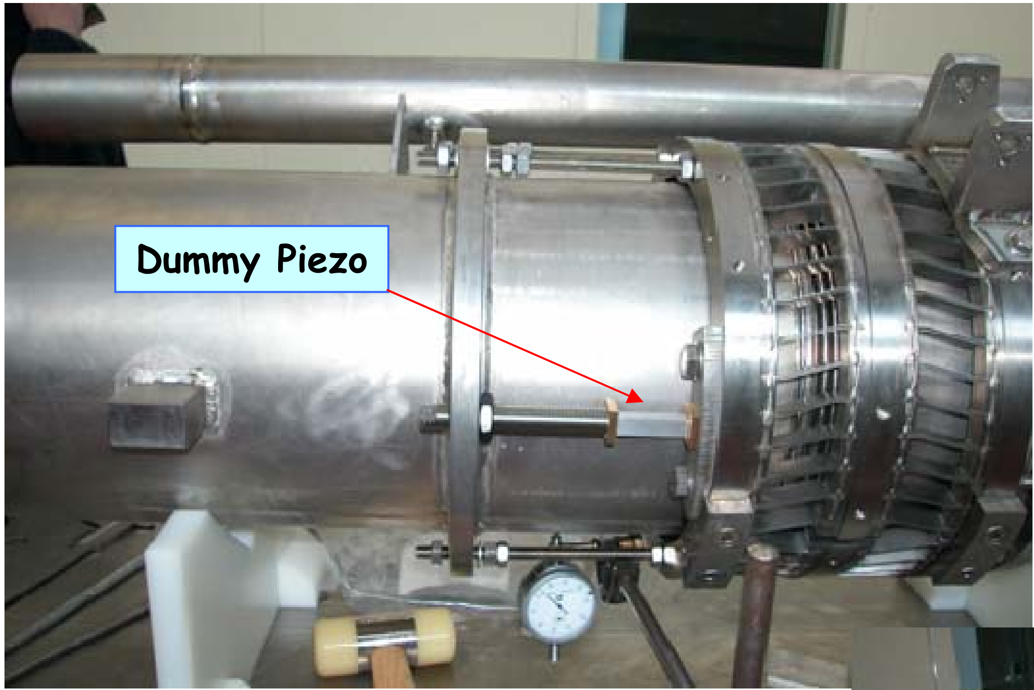
Dressed Cavity: 3D Model and Dimensions



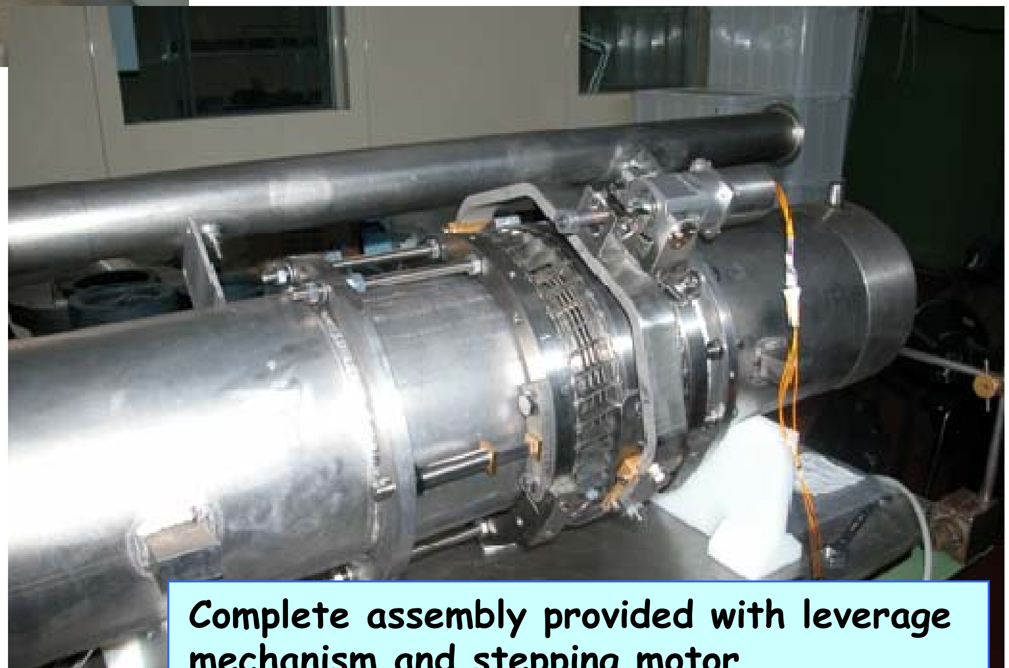


Assembling the Tuner

A. Bosotti – INFN MI – JRA1 06 Frascati



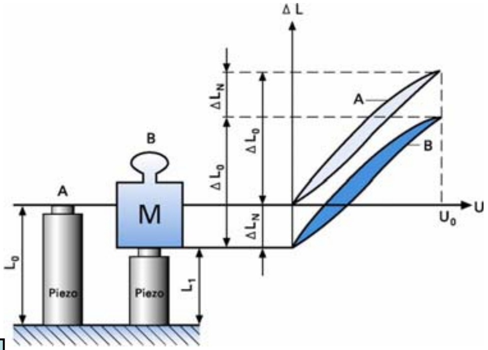
The first tests are foreseen at DESY, by the end of the year and at Fermilab in January (February) '07, in the Horizontal Test facilities, after the final tuner integration with 1.3 GHz 9-cell SC cavities.



Complete assembly provided with leverage mechanism and stepping motor

Blade Tuner Details

Requirements from the cavity point of view



± 1 mm fine tuning (on cavity) → ΔF on all piezo (sum) ≈ 3.5 kN

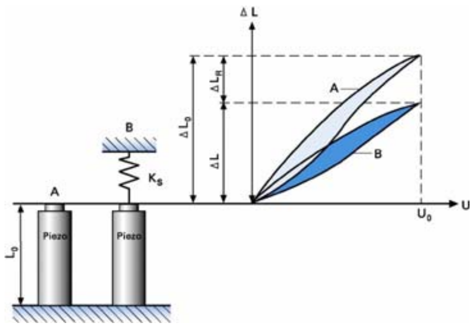
This value has to be considered as a preload variation and if, summed to set-up pre-load, the overall value is lower than the load limit of the piezo, it acts as an offset without lowering dynamic performances

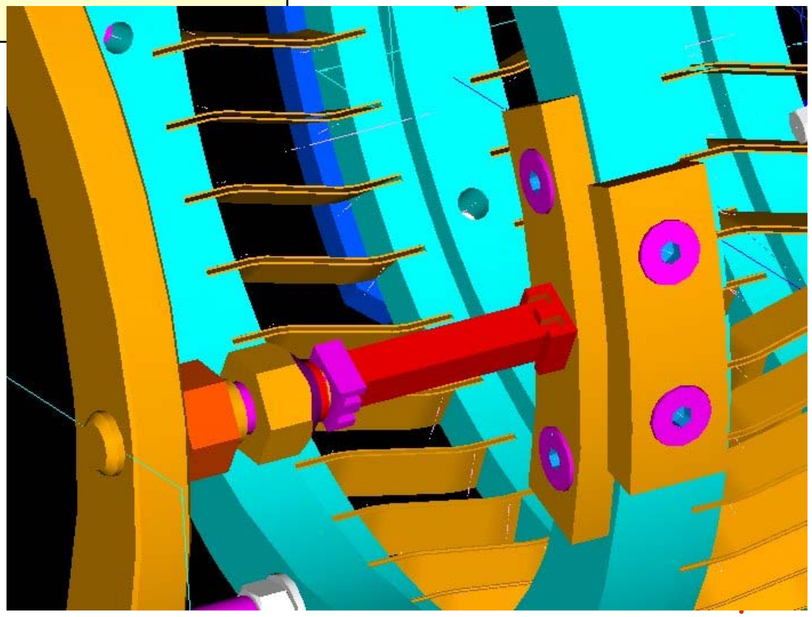
1 kHz fast tuning → ≈ 3 μm cavity displacement → ≈ 4 μm piezo displacement

This value has to be guaranteed at the temperature of 2 K, we expect to need a 40 mm long piezo (but the first tests will employ 72 mm X 15 mm^2 Noliac Piezos

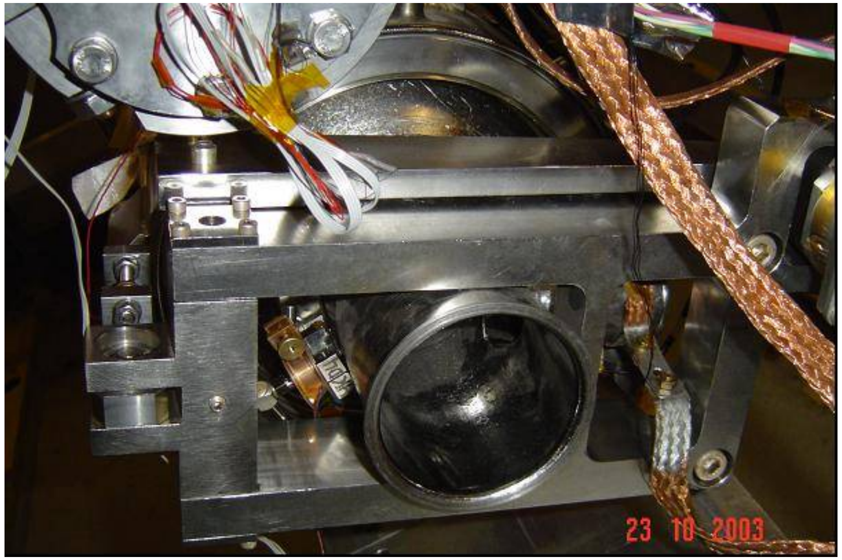
4μm piezo displacement → ≈ ΔF on all piezo ≈ 11.0 N

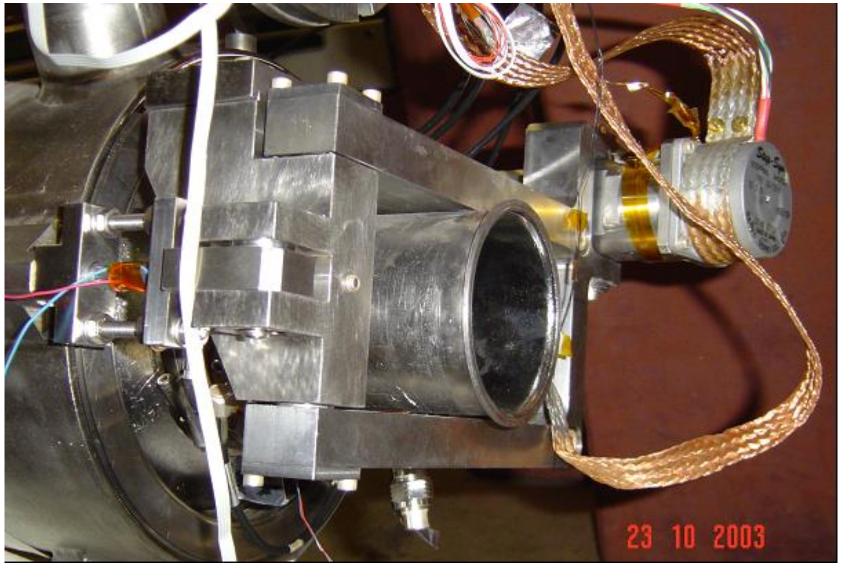
This value has been obtained in quasi-static conditions: no dynamic forces were considered

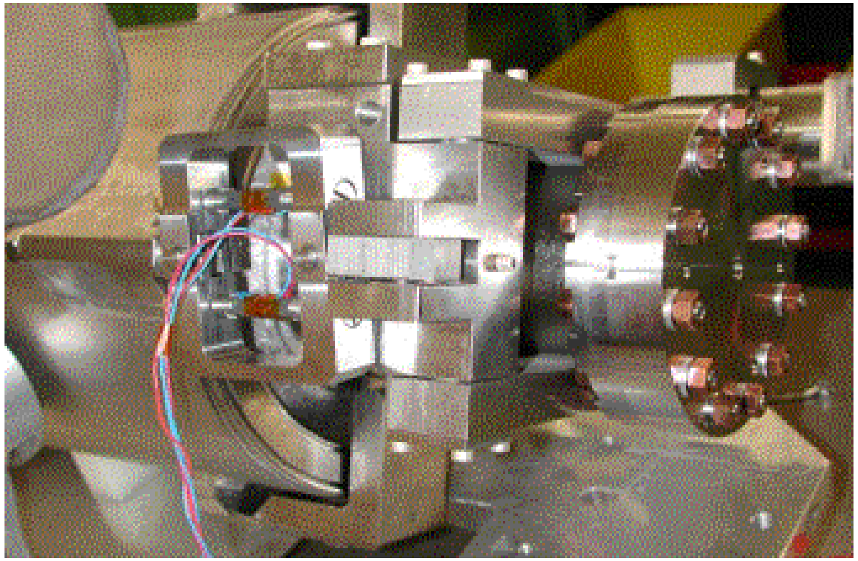




CEA Tuner

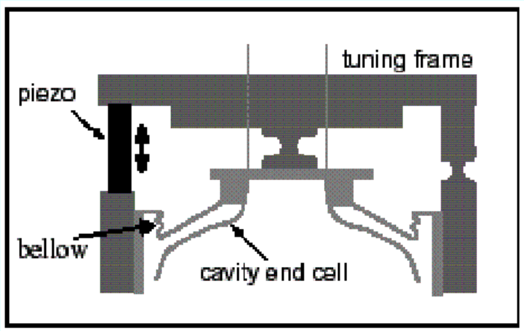






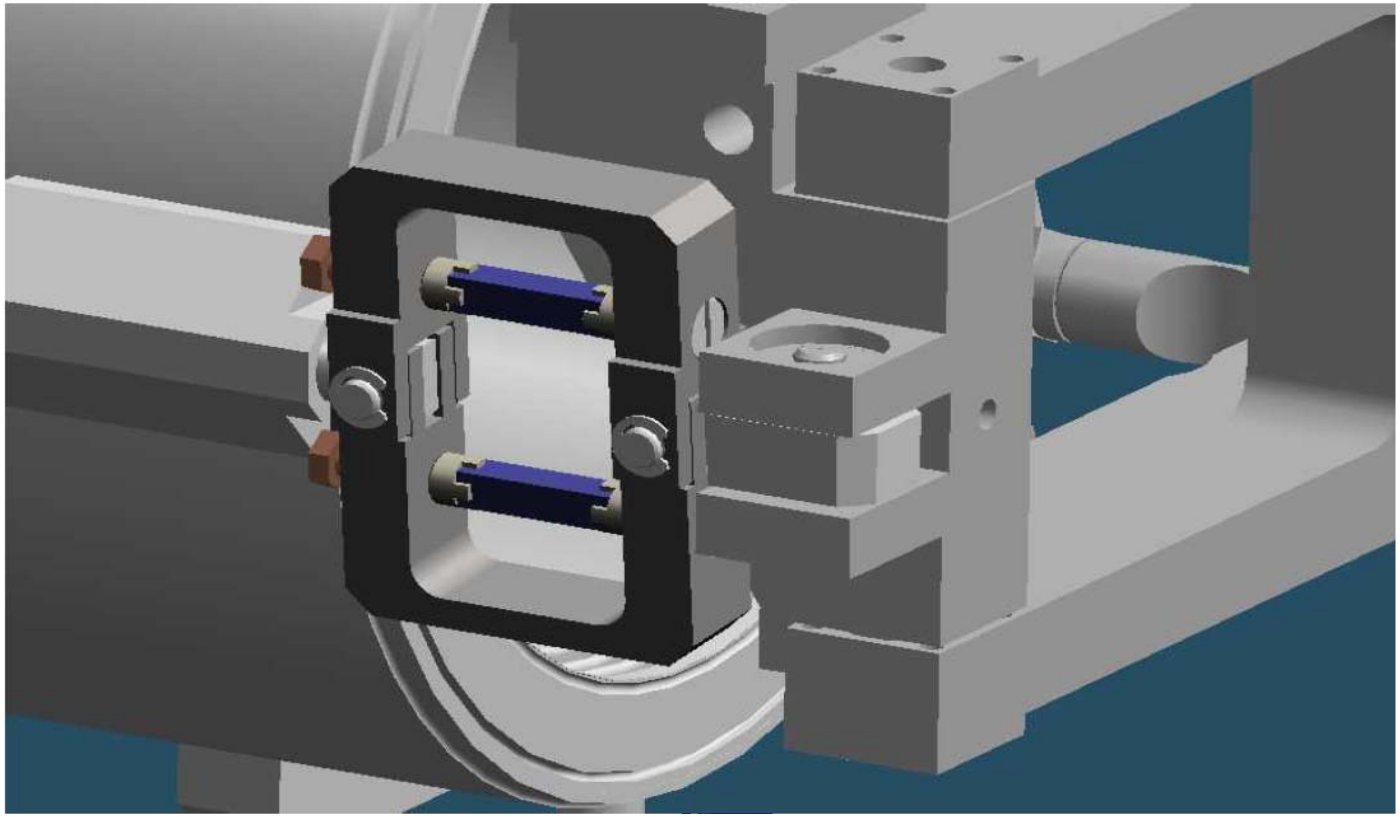
Principles of operation of tuning system

The wall thickness of the XFEL cavities has been chosen to be 2.8 mm, and the individual cells are stiffened with rings. As a consequence, the total change of the volume can be compensated by a cavity length change.



A piezoelement replaces one of the fixing rods. By applying the voltage the piezo pulls the cavity and changes its internal resonance frequency.

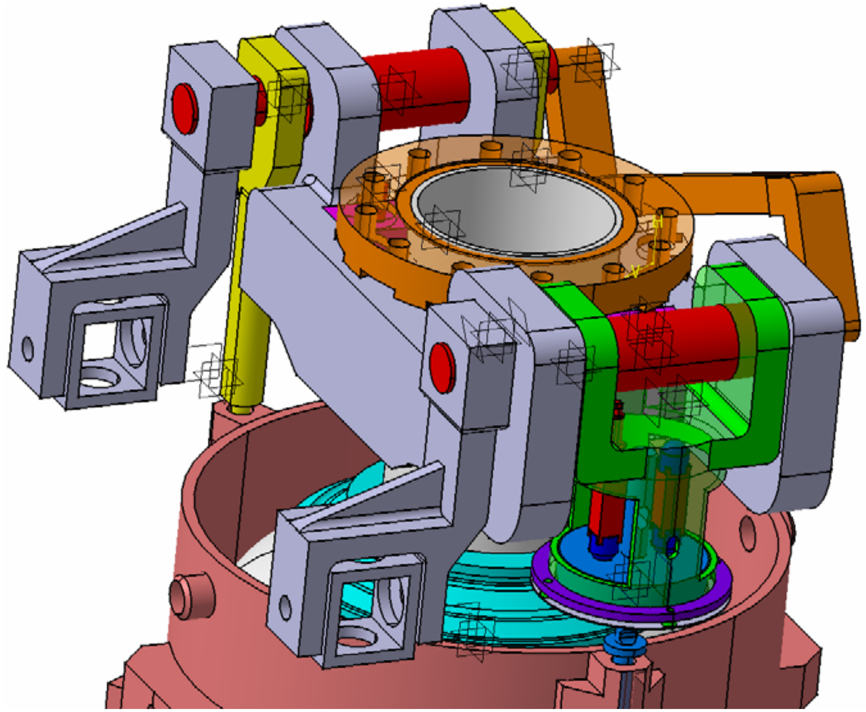
Piezos in CEA Tuner



The New Saclay Tuner for XFEL

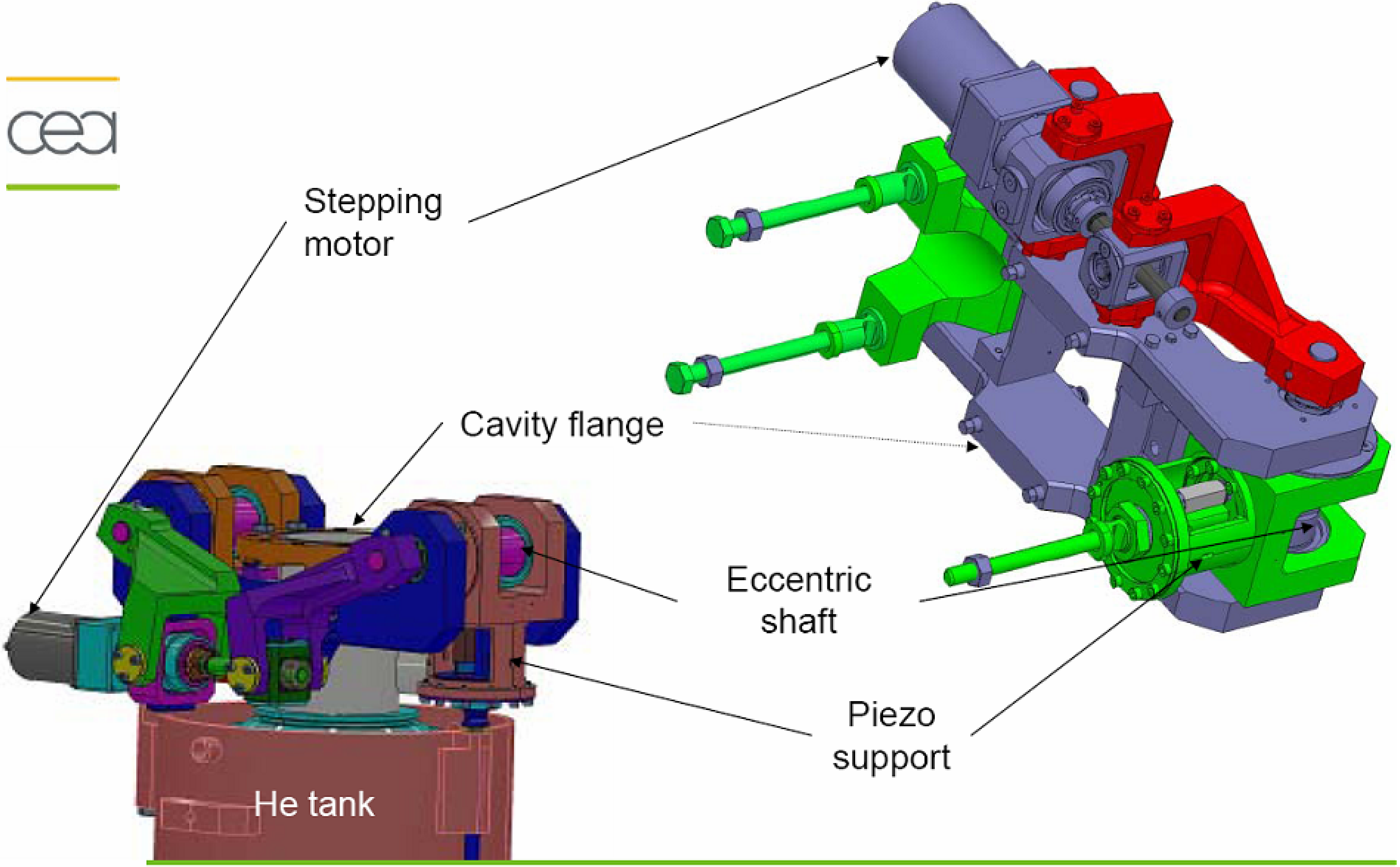
New design with piezos

- **CARE/JRA-SRF**
- **SOLEIL upgrades**
- **larger rigidity**



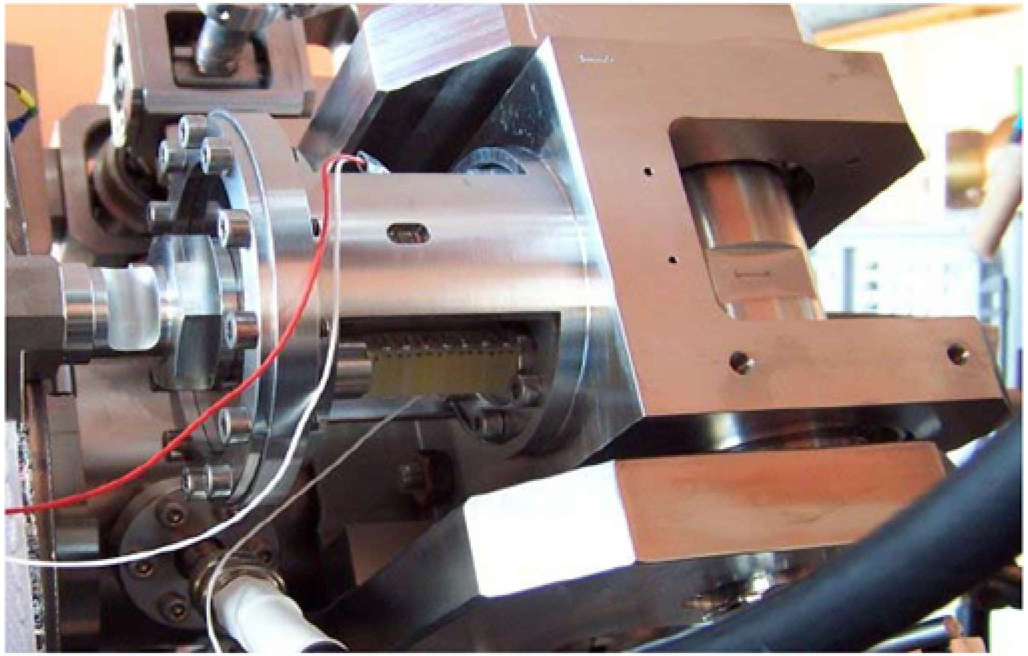
- Fabrication of 2 tuners since beginning of 2005
- 12 NOLIAC piezos, 2 PHYTRON stepping motors ordered
- Coll. with IPN Orsay: CEA send NOLIAC piezos to IPN for characterization, and IPN send P.I. piezos for tests on tuners
- Coll. with INFN-Milano for measurement with stress sensors @ 2K

The new Piezo Tuner System

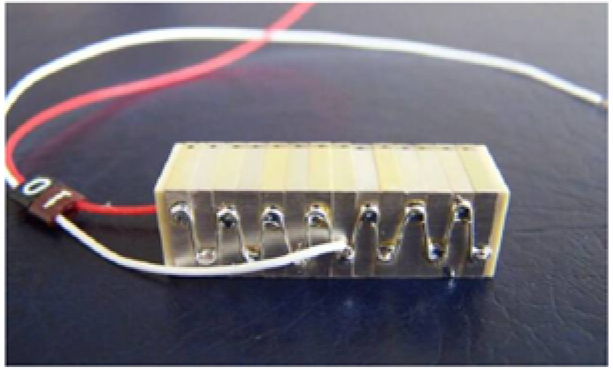


Piezo Stack Actuators

- Tests with two different piezo stacks



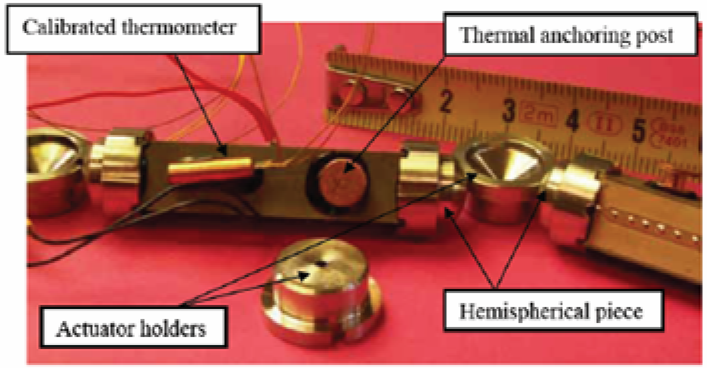
Piezo support



CEA Saclay

- NOLIAC PZT stack actuator

  L= 30 mm V_{max} = 200 V



IPN Orsay

- PICMA PZT stack actuator

  L= 36 mm V_{max} = 120 V

References for Tuners

Coaxial Blade Tuner

D. Barni, A. Bosotti, C. Pagani, R. Lange, H.B. Peters, “A New Tuner For TESLA”, Proceedings of EPAC2002, Paris, France, p. 2205.

C. Pagani, A. Bosotti, P. Michelato, N. Panzeri, P. Pierini, “Improvement of the Blade Tuner Design for Superconducting RF Cavities”, Proceedings of PAC2005, Knoxville, TX, USA, p. 3456.

C. Pagani, A. Bosotti, P. Michelato, R. Paparella, N. Panzeri, P. Pierini, F. Puricelli, G. Corniani,CARE-Note-2005-021-SRF.

CEA Tuner I & II

P. Bosland, Bo Wu DAPNIA - CEA Saclay Mechanical study of the « Saclay piezo tuner » PTS (Piezo Tuning System) CARE-Note-2005-004-SRF

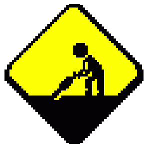
Bosland, P; Devanz, G; Jacques, E; Luong, M; Visentin, B; Wu, B - CEA-Saclay Tuners Ready for Tests, CARE-Report-06-012-SRF

The Conceptual Design Report for the TESLA Test Facility (TTF) Linac, Version 1.0

Piezo ceramics characterization

- The producers don' t supply information about the behavior of piezos at LHe temperatures and there is very few literature.

- So the piezo ceramics static and dynamic behavior at cryogenic temperatures must be investigate prior to use them in SC structures.



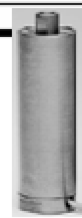
Guidelines for piezo choice	Blade tuner piezo specifications - Working point, **2K** -	Needed properties, for piezo at room temperature
Blocking force	**4 kN** open loop To guarantee almost full stroke when working against the cavity spring load	**Cross section higher then 10 x 10 mm²** blocking force is mainly not affected by temperature
Max. stroke	**4 μm** To provide the designed fast tuning range	**60 μm** **40 mm stack length** stroke reduction of 90% is considered when cooling to 2K but a margin is advisable
Stiffness	**>> 25 N/μm** To preserve the total tuner/helium tank stiffness	**k > 100 N/μm**
Control speed	**> 0.01 μm/μsec** To avoid the control loop radically exceeding actuator intrinsic dynamic	**Resonance frequency higher then 10 kHz**, with no applied load
Load limit	**> 10 kN** To avoid damaging during assembling, conditioning or cooling down	
Size	**≤ 15 x 15 x 72** To fit in the current tuner design	
Control voltage	**V_{max} < 200 V** low voltage piezo electric actuators, to limit piezo self-heating in cryogenic environment	
Long life	**1.5 10^9 cycles** Equivalent to 10 years of standard operation at 2K	No explicit guarantees from manufacturers! Only some guidelines: **Preload: 10-30% of load imit** **No tensile forces** **Vacuum, clean env.**

"Characterized" Piezos

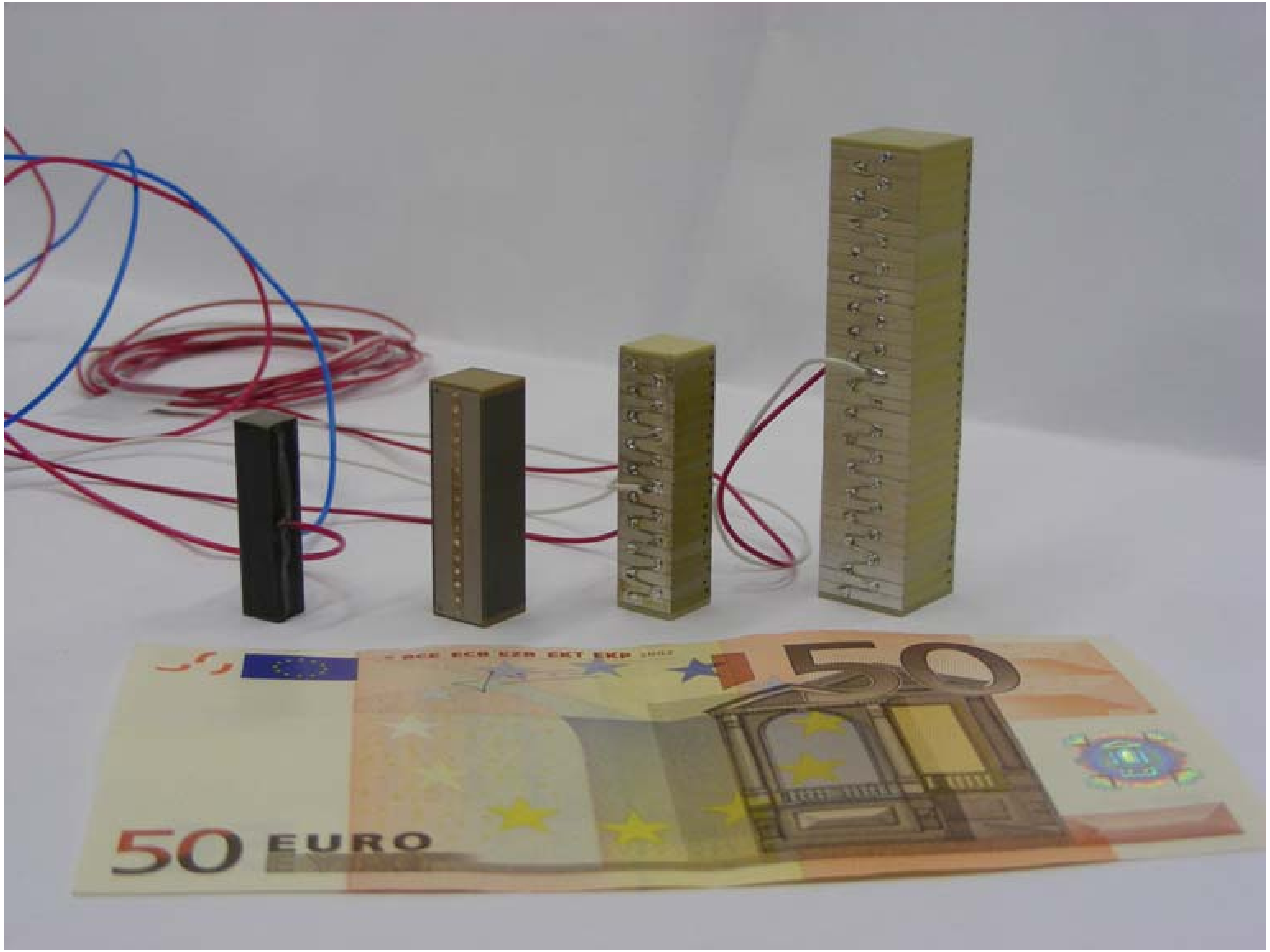
PROPERTIES	unit / tolerance	Noliac	Noliac	Epcos	PI	Noliac	Piezomechanik
		SCMA/S1/A/10/10/40/200/60/4000	SCMA/S2/A/15/15/70/200/100/9000	LN 01/8002	P-888.90	SCMAS/S1/A/10/10/30/200/42/6000	Pst 150/10
Room Temperature							
material		medium soft doped PZT-S1	medium soft doped PZT-S2	PZT-nd34	PZT-PIC 255	medium soft doped PZT-S1	
case/preload		no	no	no	no	no	Yes / 400N
length	mm	40 ± 0,5	70 ± 0,8	30	36	30 ± 0,5	64
active length	mm	38.5	68.5		33.84	27.5	
cross section	mm x mm	(10 x 10) ± 0,2	(15 x 15) ± 0,3	6,8 x 6,8	10 x 10	(10 x 10) ± 0,2	
Number of layers		266	490		300	196	
Average layer thickness	um	140	140		113	140	
Young modulus	kN/mm2	45	47	51	48.3	45	
stiffness	kN/um	0,1125	0,151	0.083	0.105	0.15	0.035
max. stroke	µm	60 ± 9	100 ± 13	40	35 ± 3,5	42 ± 6,3	80
blocking force (open loop)	N					6000	3500
blocking force (closed loop)	N	4000 ± 800	9000 ± 1400	3200	3600 ± 720	4000 ± 800	
max. load	N	12000	27000		10000	12000	
Parallel Res. Frequency @ no load	kHz	38		52	40	51	
density	kg/m3	7,7 x 10^3	7,5 x 10^3	7,75 x 10^3	7,8 x 10^3	7,7 x 10^3	
min. voltage		0	0	0	-20	0	-30
max. voltage	V	200	200	160	120	200	150
control speed - unloaded	V/µs			1.6			
charge current	A			20			
capacity: nominal	µF	8	40	2.1	12.4	5.7	
measured	µF	8.3		2.5	13.6	6.2	
Loss Factor	tanδ	0.017		0.019	0.015	0.017	
Thermal Expansion Coefficient (Multilayer)	Ppm/K	-2.5				-2.5	
Cryogenic Measurements, T = 4.2 K							
Parallel Res. Frequency @ no load	kHz			62	48.5	60	
Capacity @ no load	µF				5.7		
Cryogenic Measurements, T = 2 K							
Parallel Res. Frequency @ no load	kHz				52.5		
Capacity @ no load	µF				3.5		
Expected Values							
Capacity @ T = 4.2 K	µF			0.125		0.31	
Capacity @ T = 2 K	µF	1	4				
Stroke @ T = 4.2 K	µm	7	12	8	7	8.4	16
Stroke @ T = 2 K	µm						
Parallel Res. Frequency @ no load, T = 4.2 K	kHz	46					
Parallel Res. Frequency @ no load, T = 2 K	kHz	50					



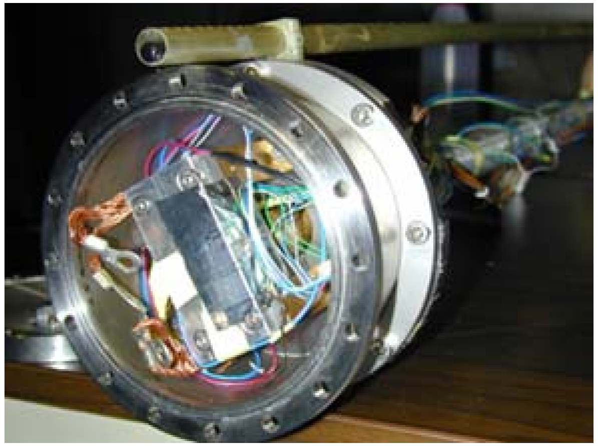


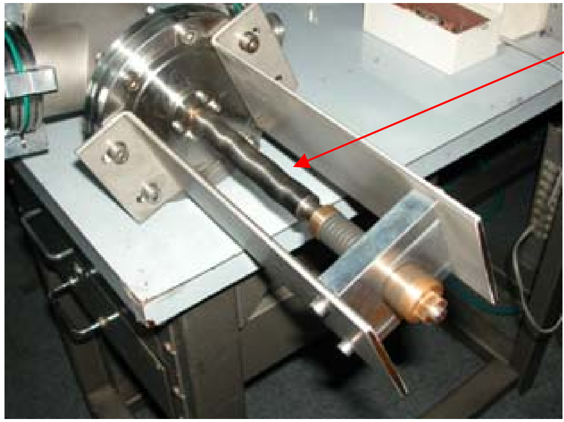


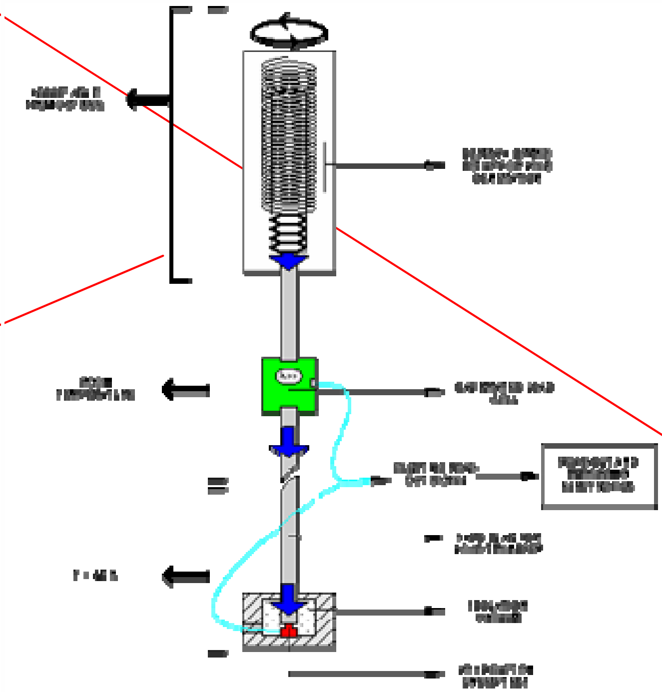
Piezos “involved” in LLRF operations



Devices calibration "facility" example

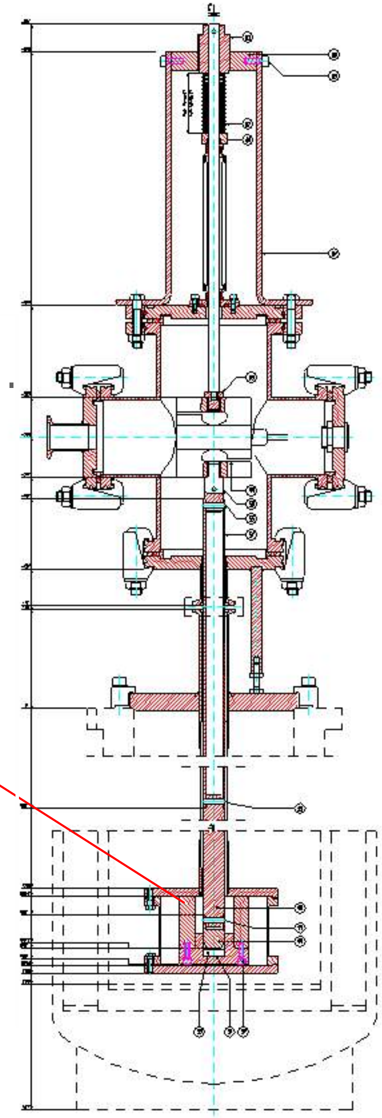






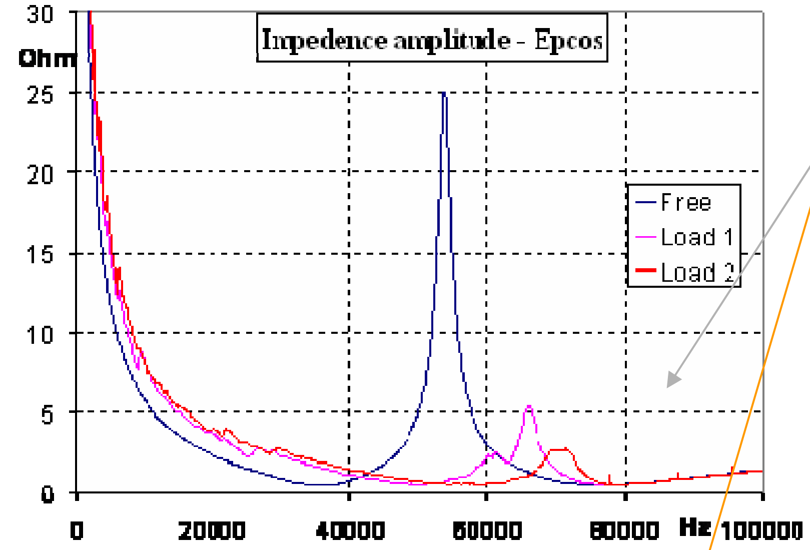
How the force on the DUT is generated

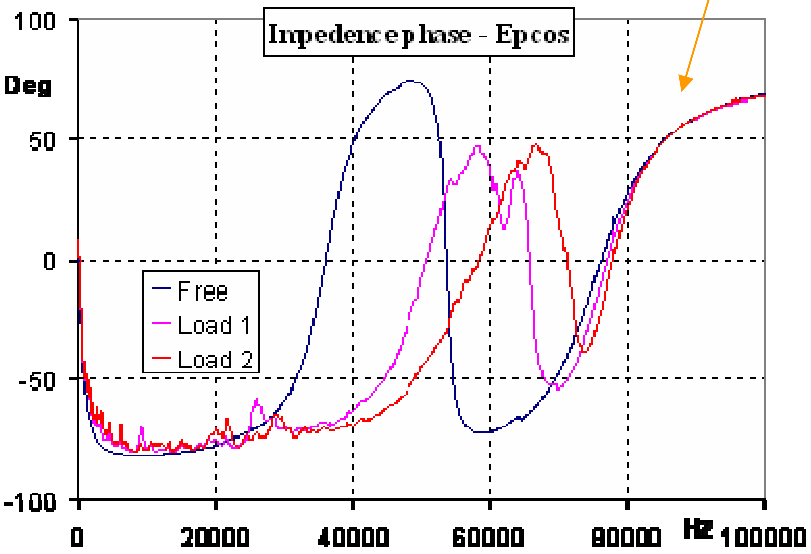
Insert Drawing



Indirect measure of preload

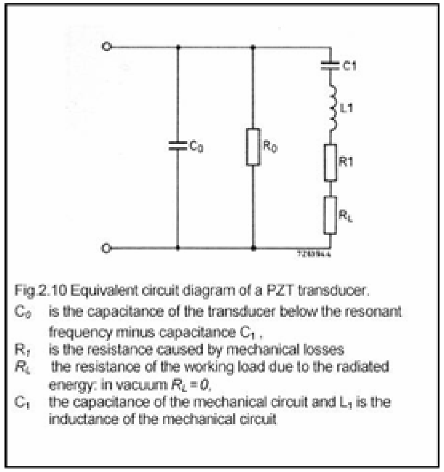
Indirect measure of the preload on piezoelectric actuator:
the position of some resonances in the piezo impedance is linked to the applied force





Measurements of $Z_{PIEZO}(f)$ made at LASA with *growing load*

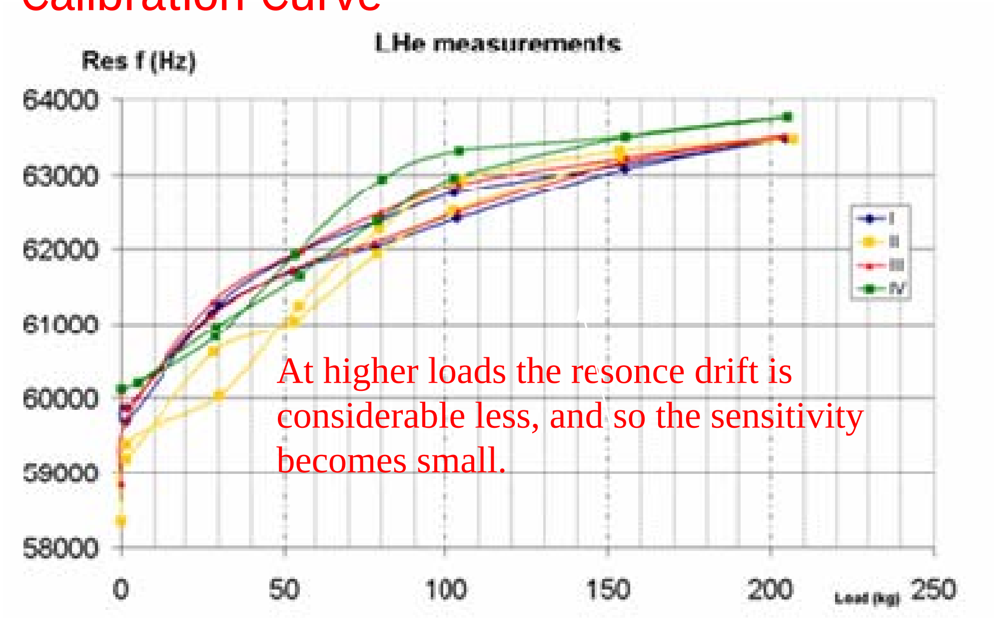
Scheme of the setup used



Piezo circuital model (Van Dyke)

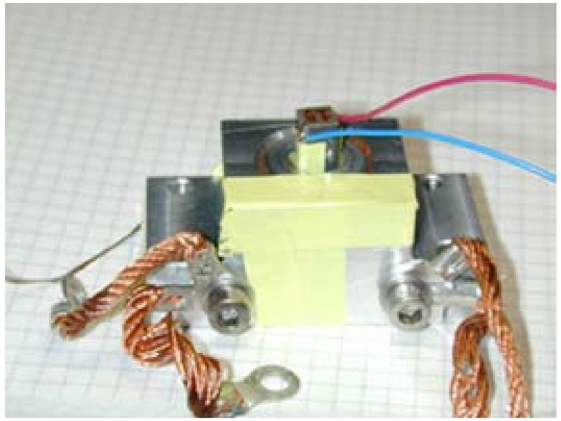
Piezo resonance frequency response vs applied load

Calibration Curve

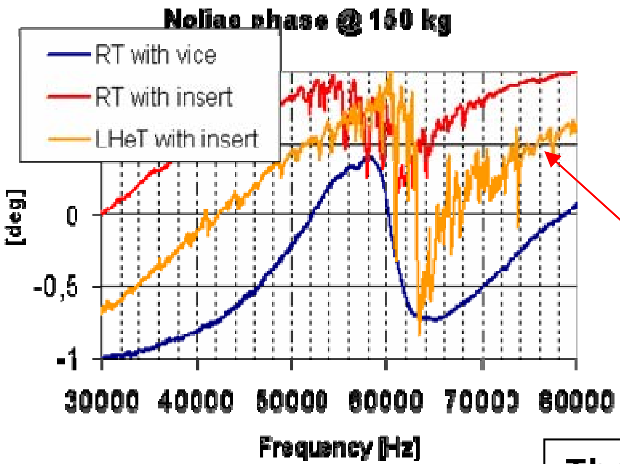


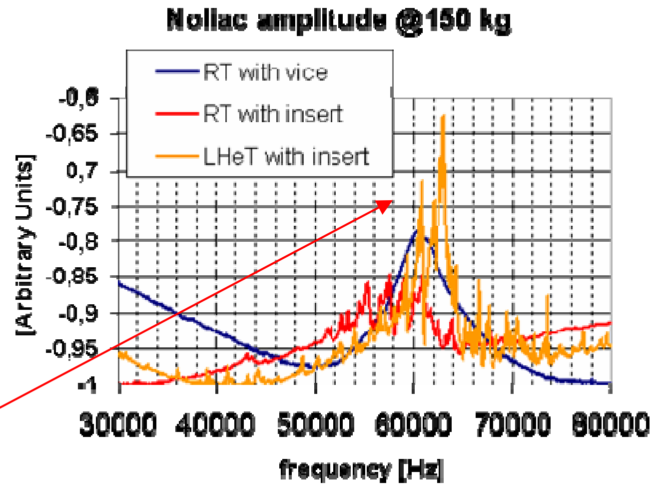
At higher loads the resonce drift is considerable less, and so the sensitivity becomes small.

Each piezo to be tested is hosted in a properly shaped aluminium support to avoid any non-vertical force component on the ceramic element;



the support element is then fixed inside the cold box





The interaction between the piezo and the mechanical supports generates other resonances(?) that meke difficult to follow the piezoceramic proper resonces drift with incresing load.

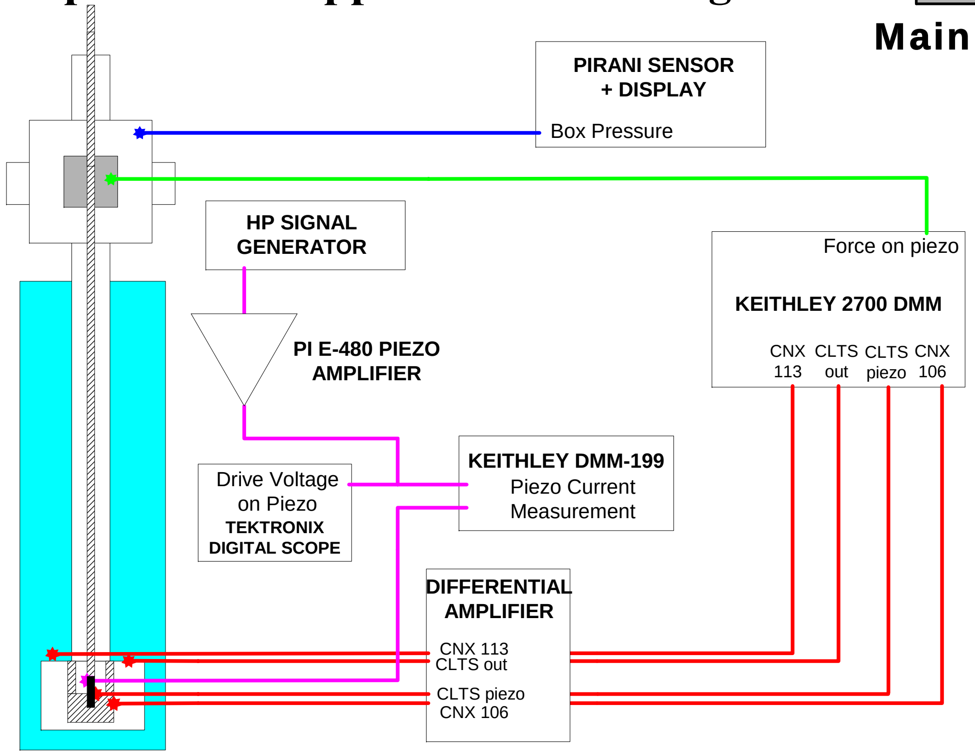
Piezo Life-Time Test 1/2

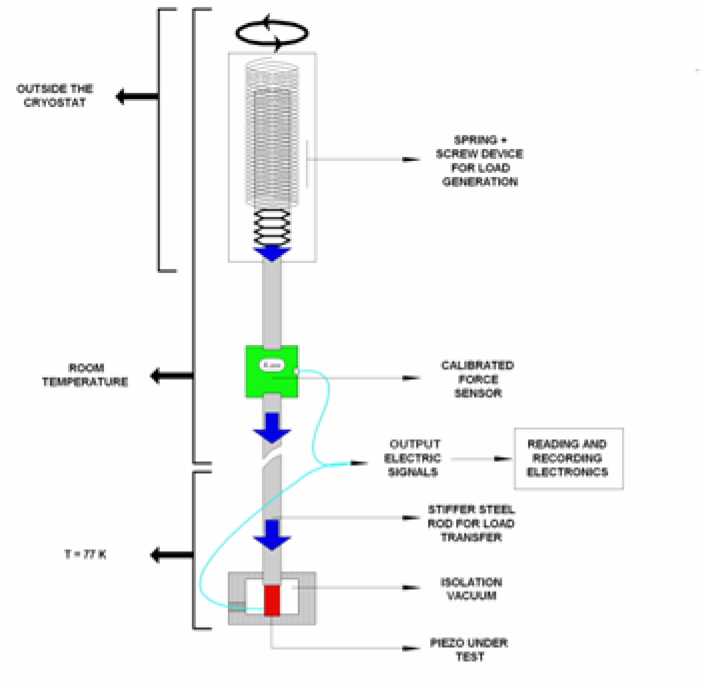
The purpose of this test is to investigate the behavior of piezoelectric ceramics in condition equivalent to 10 years of operation as actuator in active frequency tuner for ILC superconducting cavities (SC).
To do this a **Physik Instrumente PI P-888.90 PIC255** piezoelectric ceramic has been cooled down in LN2 and has been excited uninterruptedly for about one month up to its limits, sustaining about 1.5×10^9 cycles of switching, up to nearly the maximum stroke, a good estimate of ten years as actuator for ILC cavities.

PROPERTIES	PI P-888.90	Unit
Material	PZT-PIC 255	
Length	36	mm
Cross section	100	mm^2
Max. stroke	35	μm
Blocking force	3600	N
Res. frequency @ no load	40	kHz
Min. voltage	-20	V
Max. voltage	120	V
Capacity - nominal	12,4	μF
Capacity - measured	13,6	μF

Main features and parameters of the piezo

Experimental apparatus block diagram





Insert "functional" scheme

Piezo Life-Time Test 2/2

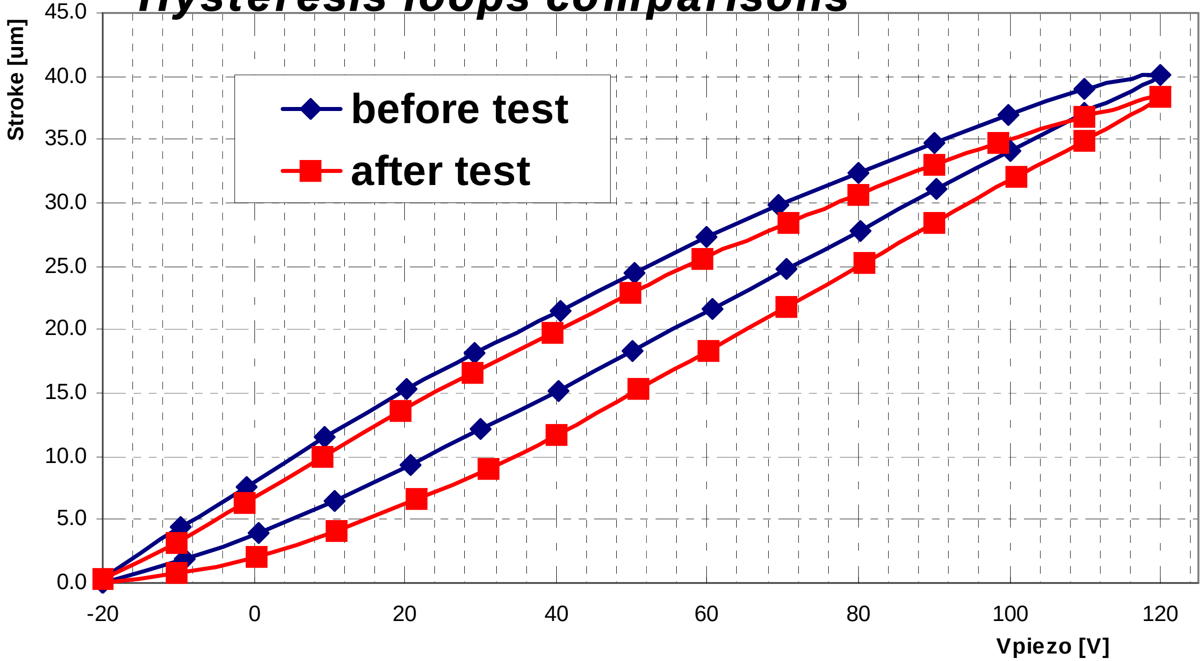
	Before	After
Capacity [uF]	**13.6**	**13.56**
Res. Freq [kHz]	**45.9**	**45.2**
Max stroke [um]	**40.2**	**38.3**

Main piezo parameters checked

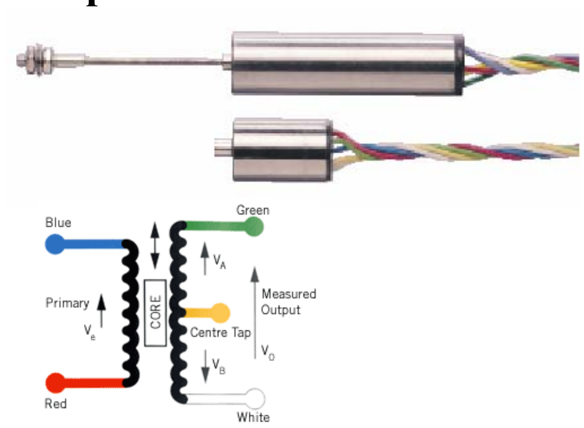
Start	**26 Nov 2004**
Stop	**20 Dec 2004**
Hours	**622**
Cycles	**1.505×10^9**
Sine Wave Amplitude	**-20V ÷ +120 V**
Frequency	**117 Hz** for 4 days **497 Hz** for 6 days **997 Hz** for 16 days
Average Preload	**1.25 kN**
Max Current [rms]	**< 200 mA**
Average Temperature	**81 K**

Main features of the life time test

Hysteresis loops comparisons



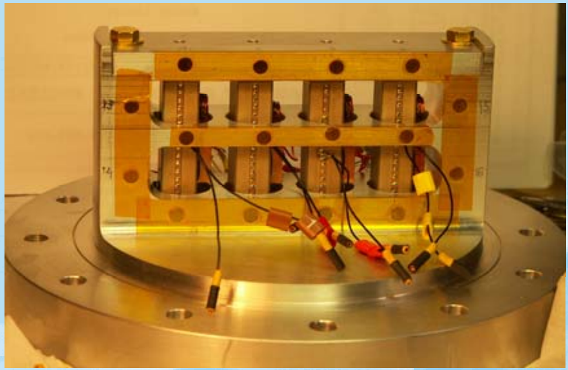
Solartron SM1 LVDT position transducer

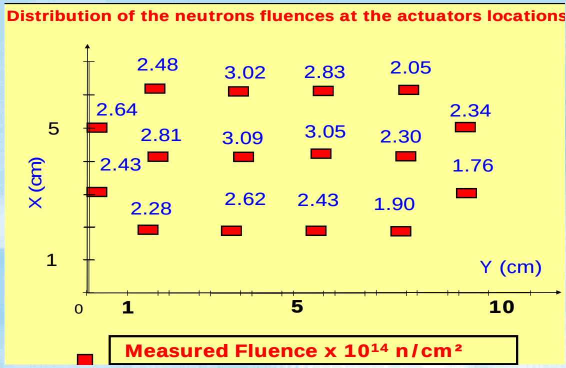


Sensitivity@20kHz

σ = 149 mV/V/mm

Radiation Hardness tests with fast neutrons at T=4.2 K

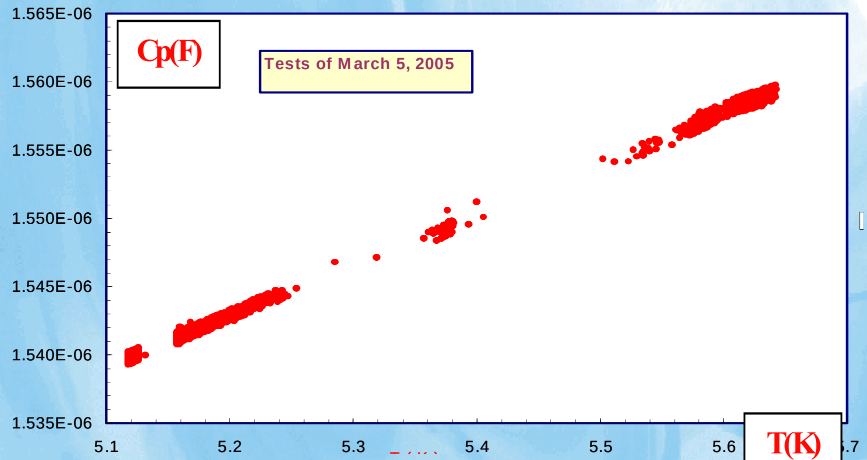




Test stand for 4 PICMA actuators and measurement of total dose distribution ($x10^{14}$ n/cm²)

Irradiations insert in front of the beam-line

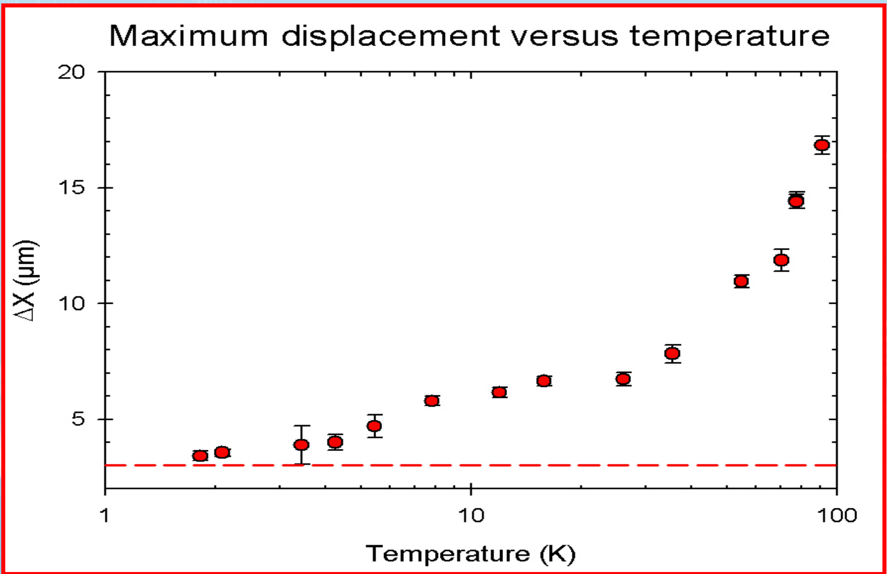
A total Dose of ~ 2-3.10^{14} n/cm² in 8h exposure to beam

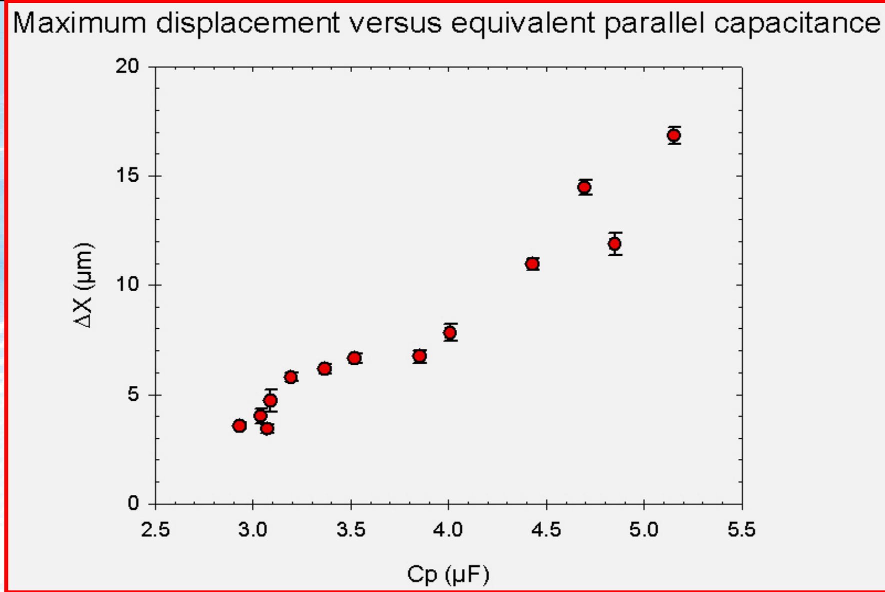


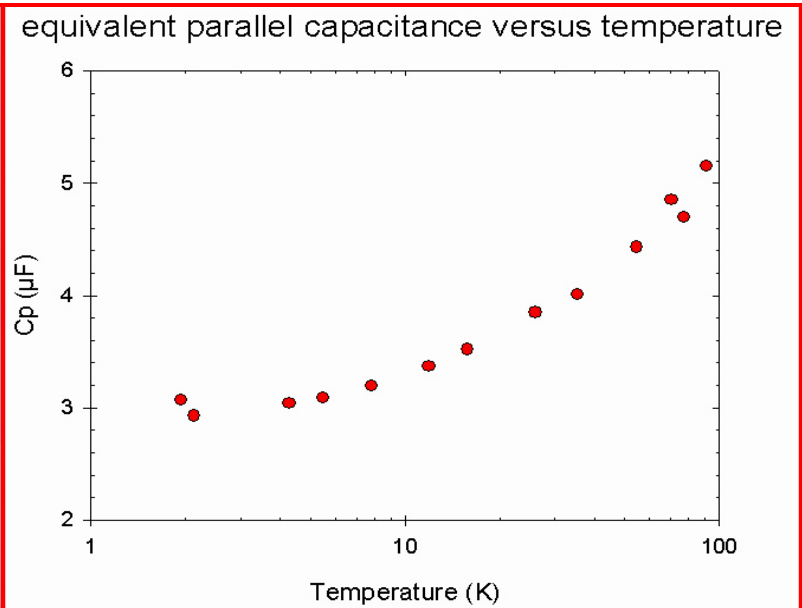
No anomalous behavior, no damage observed during irradiations with fast neutrons in liquid helium (T=4.2 K)

Radiation tests finished: 3 Runs performed, 11 actuators evaluated

Test results for PICMA#01 actuator







19/10/2005

1) Maximum displacement <u>at 1.8 K > 3µm</u>

Actuators suited for TESLA cavity Lorentz detuning compensation (~1kHz)

2) No electrical breakdown and no damage observed during the tests

Life time

3) Strong correlation between capacitance and maximum displacement

A simple mean for calibration of a large number of actuators

Piezostack characterization – summary

Dimensions: **10x10x36mm**
Manufacturer: **PI**

Dimensions: **10x10x30mm**
Manufacturer: **NOLIAC**

Maximum displacement (stroke) at 1.8K >3μm

Actuators suited for **VUV-FEL**, **X-FEL** and even **ILC** (≈1kHz⇔~35MV/m)

No damage and no electrical breakdown observed during all tests

Lifetime at LN_2>1.5*10^9 cycles (INFN)⇔5Hz for 10 years of operation

No damage caused by neutron irradiation, only heating observed

Dose of 2-3*10^{14} n/cm² in 8h

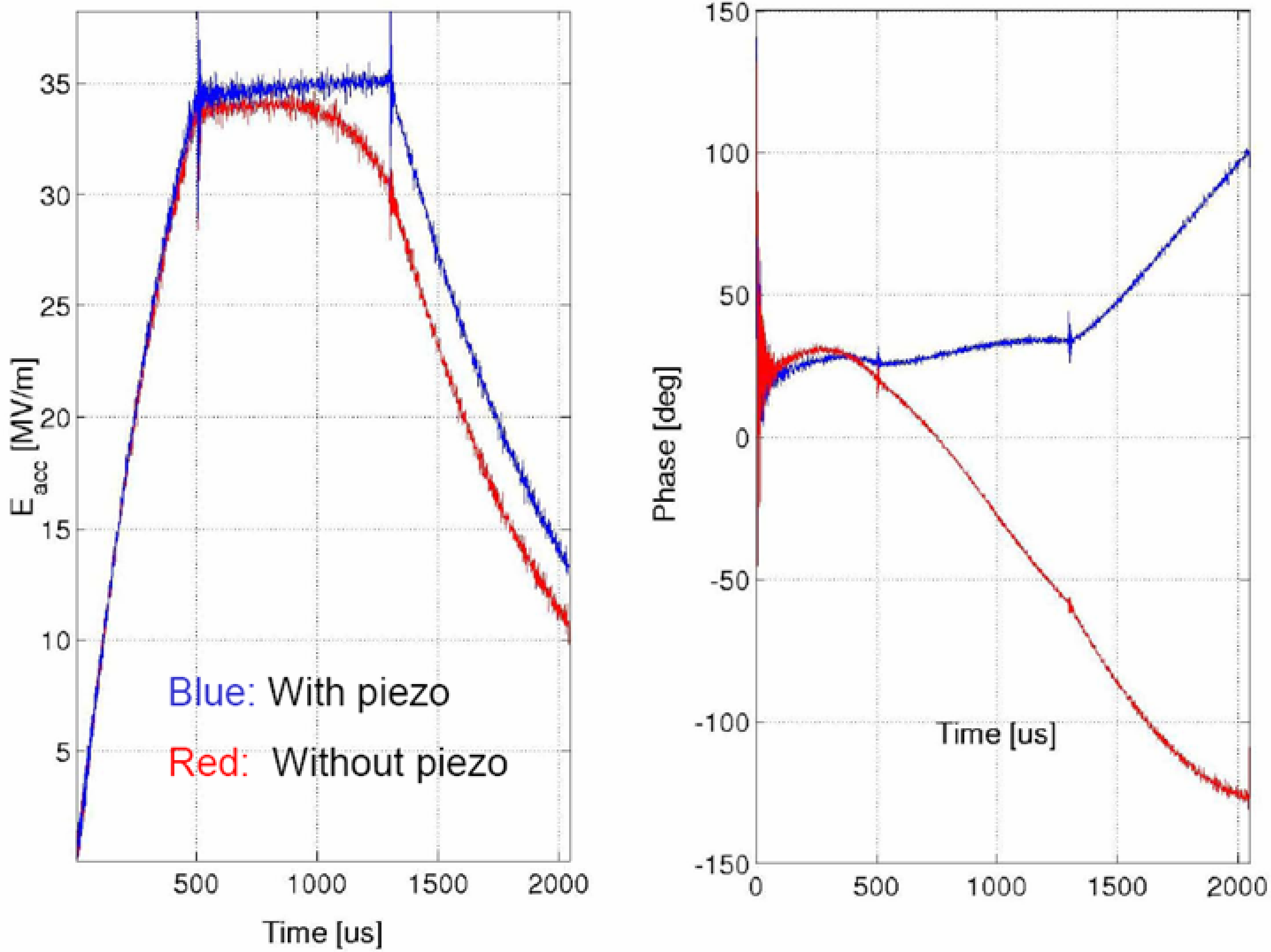
Facility for piezostack investigation is set in IPN Orsay and INFN Milan

Piezos in operation

- FLASH at DESY (piezos inserted in cav #5 of module 1 tuner)
- CHECHIA at DESY
- CryHoLab at CEA Saclay
- CMTS at DESY (Cryo # 6 $\Rightarrow$ 8 cavities equipped with fast tuners)

Test In CHECHIA

RF Signals at 35 MV/m

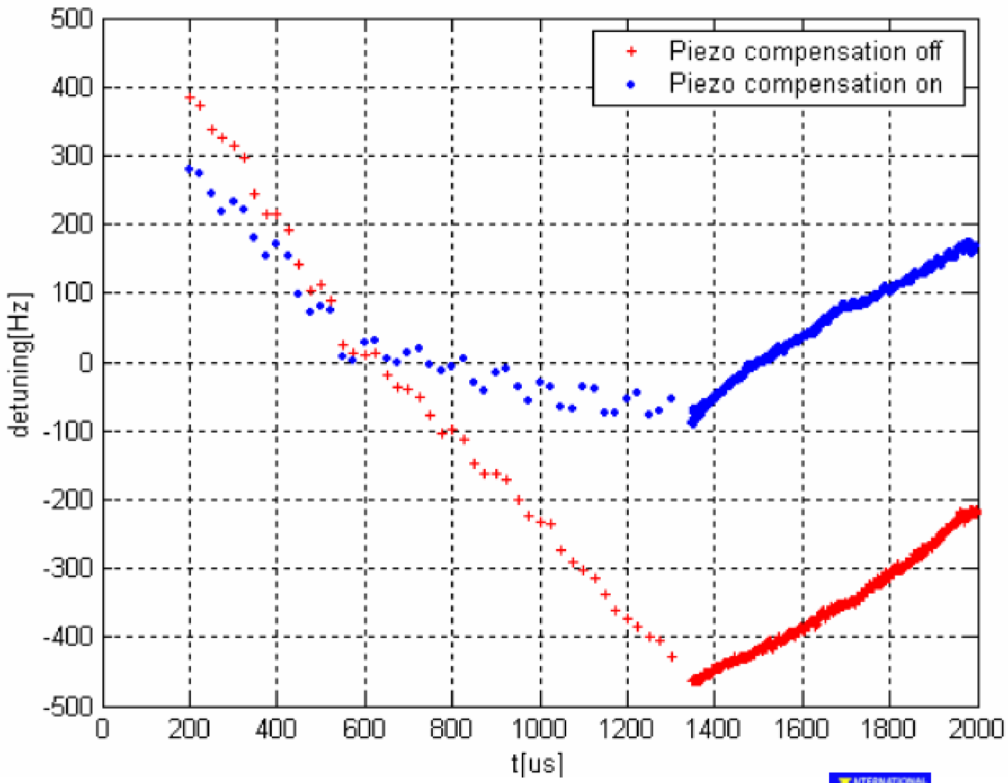


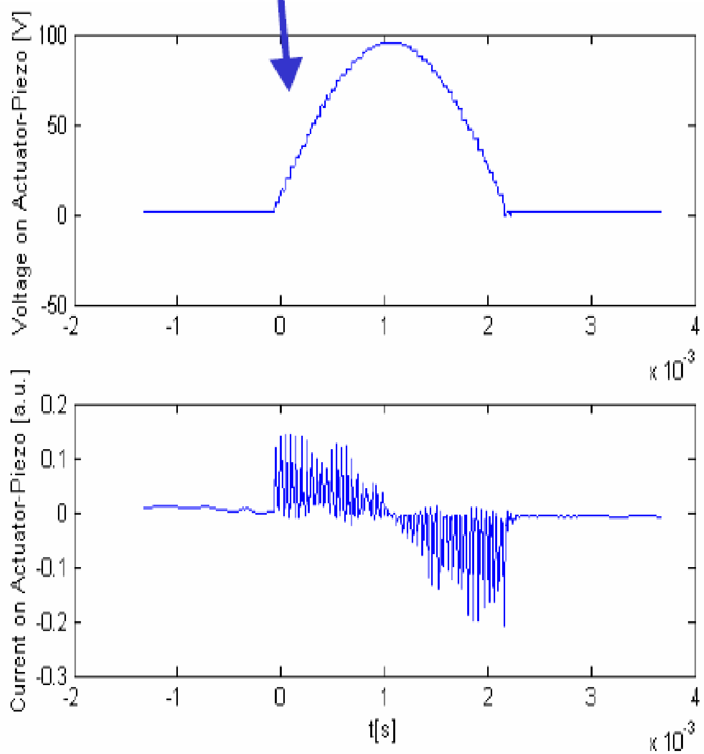
Frequency stabilization during RF pulse using a piezoelectric tuner

Blue: With piezo

Red: Without piezo

Frequency detuning of 500 Hz compensated voltage pulse (~100 V) on the piezo. No resonant compensation

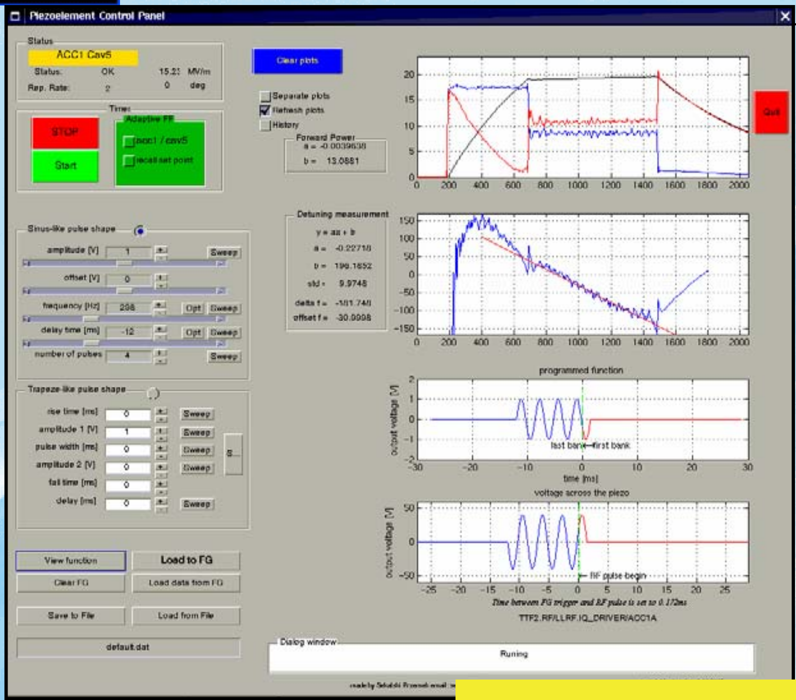




Lutz Lilje DESY -MPY-

07.03.2005

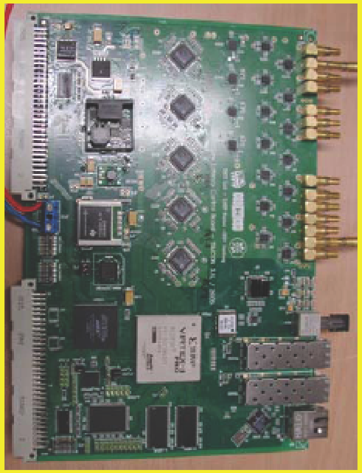
Piezo Tests in FLASH

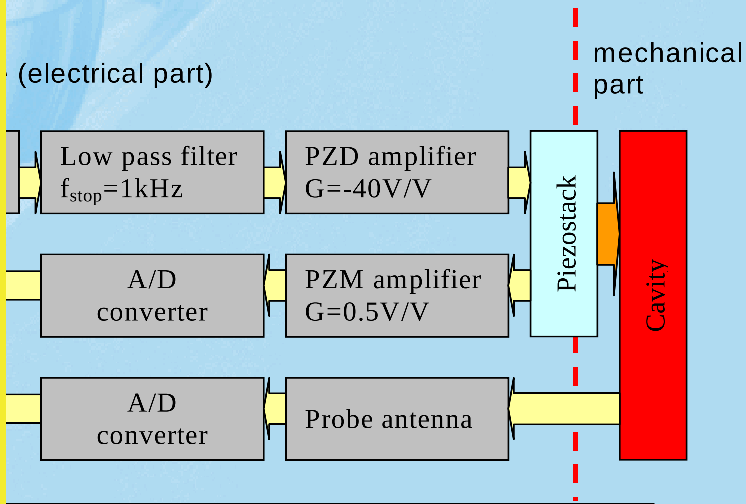


Piezo Control Panel
Control panel is implemented
in MATLAB and in the DSP board.

Final goal is to integrate
the algorithms with LLRF system
in FPGA

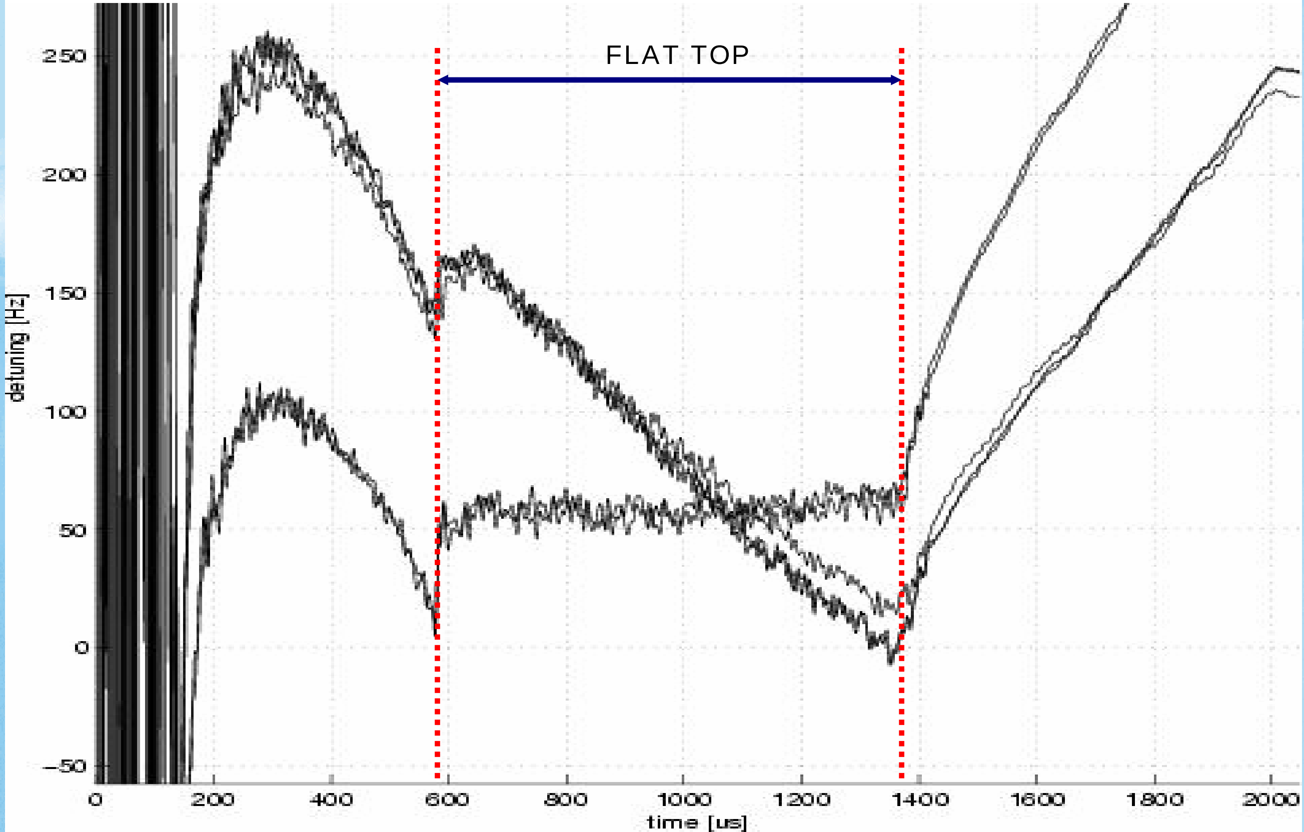
Algorithms implemented
in SimCon board





Results

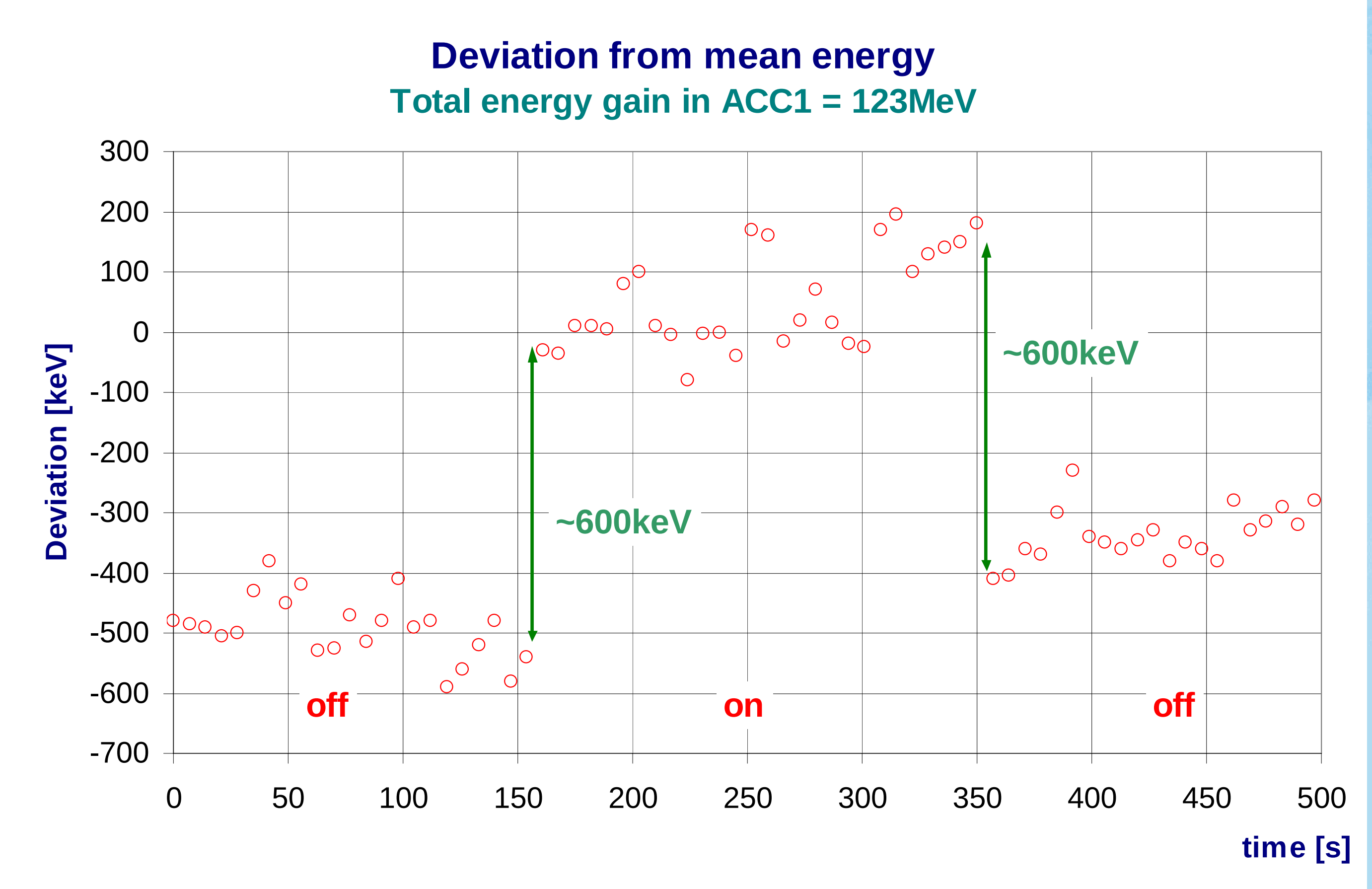
Detuning without piezo compensation ≈ 180Hz
Detuning with piezo compensation < 10Hz



Measurement done in cavity 5, ACC1 VUV-FEL

field gradient ~20 MV/m

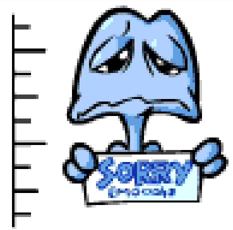
Result of beam energy drift



The energy increases by almost **600keV** (or **0.5%) due to the fast tuner applied to only one cavity** (cav5/ACC1).

The drift is caused by the klystron. Feedback in ACC1 was switched off.

EPCOS breakdown



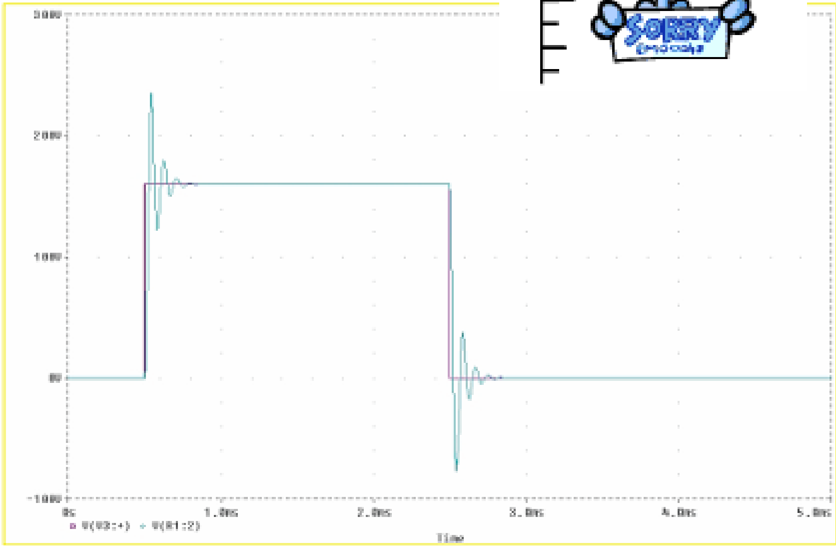
Due to the long pulses the thermal protection of the amplifier was turned on.

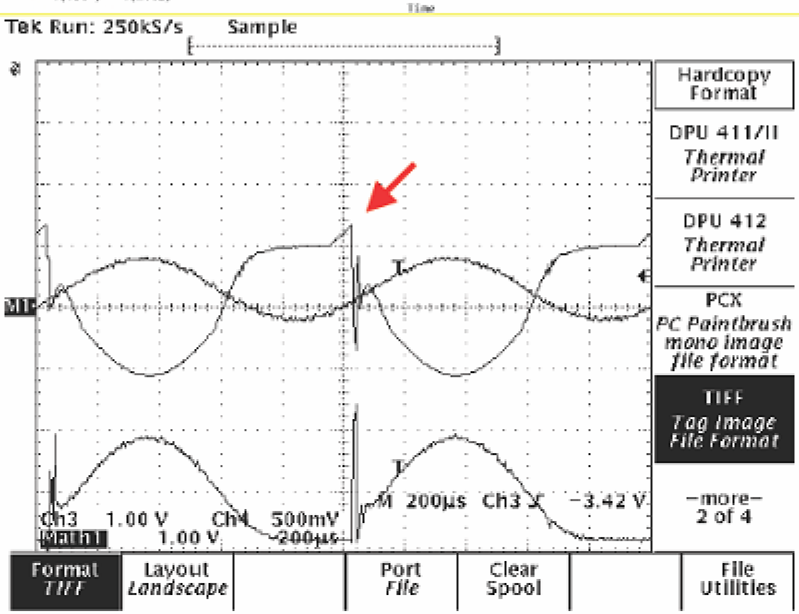
↓

The output voltage was cut off and the step function was applied to the circuit.

↓

The over-voltage cause the piezoelement breakdown.



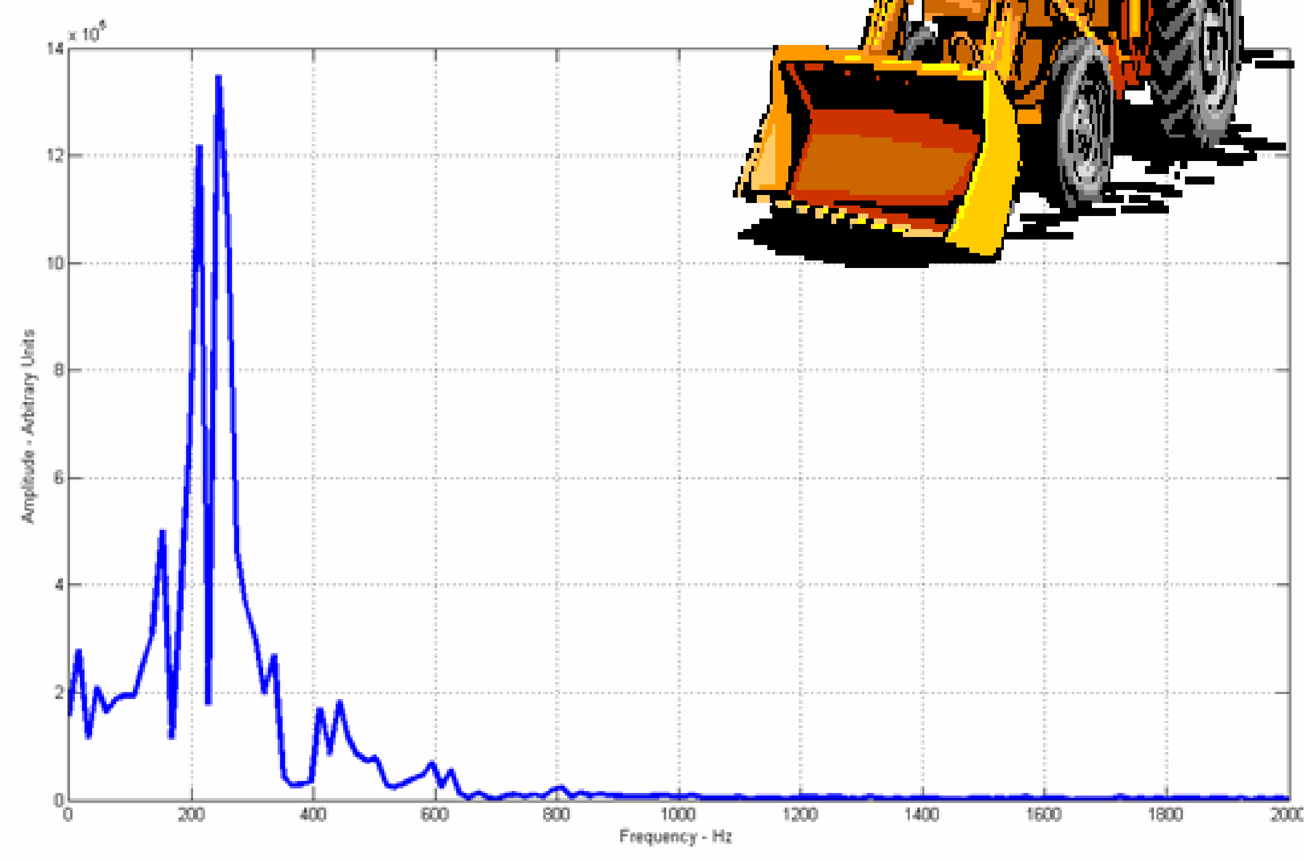


Tests On Module # 6 cavities in CMTB at DESY (work in progress!)

The eight cavities inserted in cryomodules # 6 are equipped with active tuners with 2 PI piezos

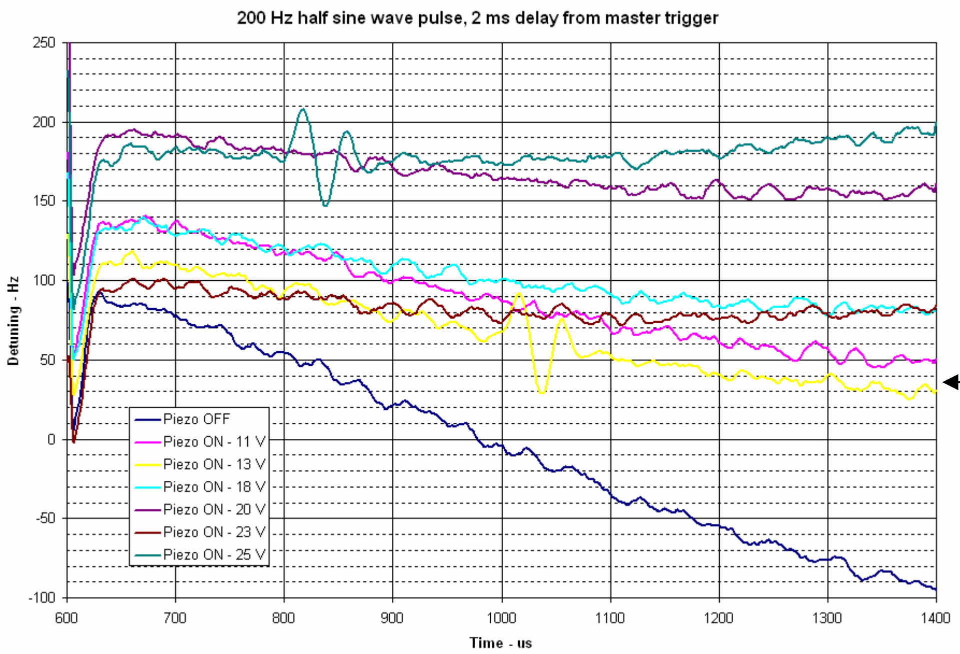
Analysis of the cavity ringings

While the module was operated at 20 MV/m, 10 Hz rep. rate, the cavity oscillations induced by the RF pulse was recorded using the piezo as a sensor, then the corresponding spectrum has been computed showing an estimation of the RF-to-Piezo transfer function



LFD compensation on CMTB cav3

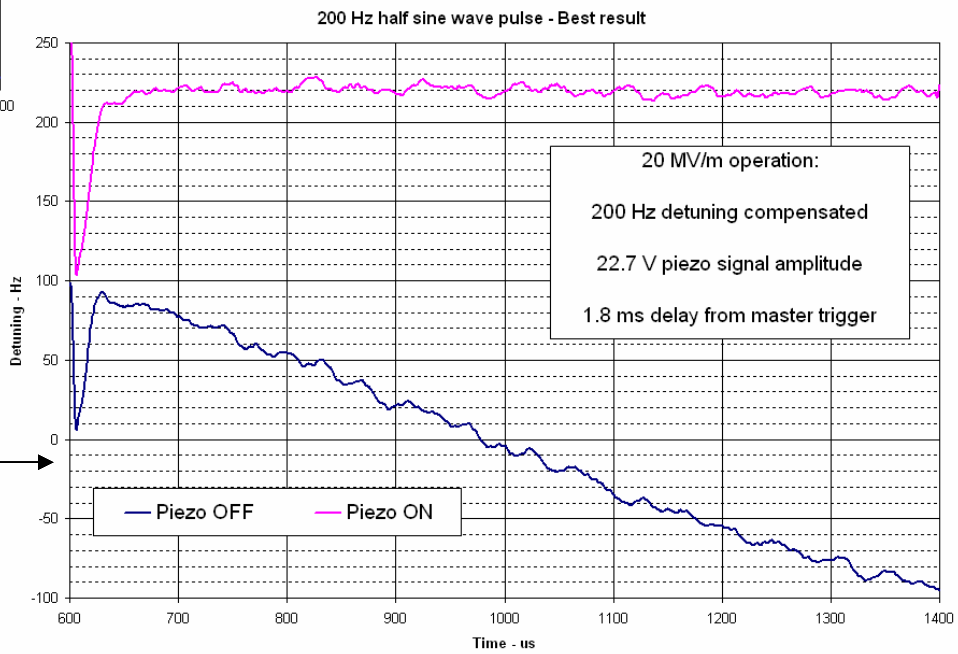
While the module was operated at 20 MV/m, 10 Hz rep. rate one piezo has been used to compensate the detuning of the cavity during the flat-top, therefore leaving a static detuning value.



The delay of the piezo pulse from the master trigger has been set to a safety value of 2 ms, that correspond to a time window of 440 μs between piezo and RF pulse.

The the amplitude of the piezo pulse has been raised. **The compensating effect is visible**. Even an over-compensating effect of the piezo pulse can be seen at higher amplitudes

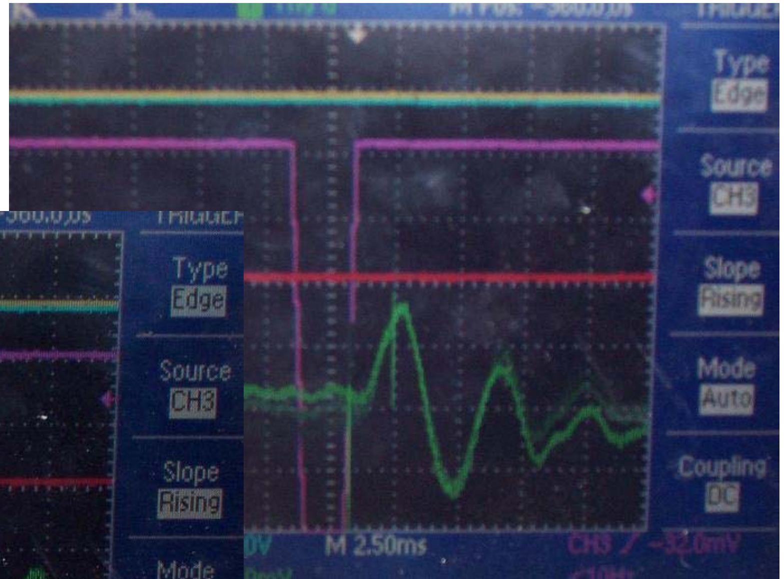
Then both amplitude and delay of the piezo pulse has been swept around in order to obtain the best detuning compensation. **The best result is shown**, it corresponds to a **piezo pulse amplitude of 22.7 V and to a time window of 640 μs between piezo and RF pulse** (1.8 ms delay from master trigger).



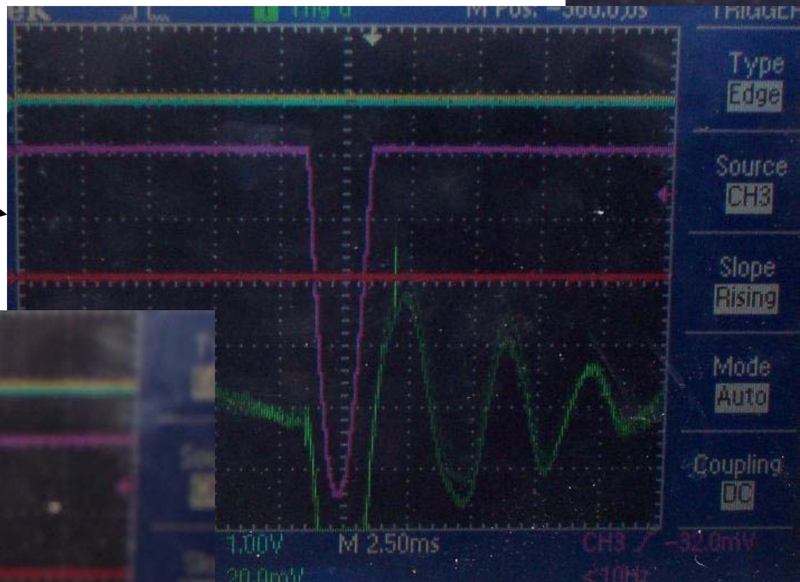
Scope traces during LFD compensation

The traces of the scope in use during these measurements are shown. The 2 visible traces of interest are the violet one, **the actuator piezo signal** (the piezo driver input signal), and the green one, **the readout from the sensor piezo** (the output of the differential amp.)

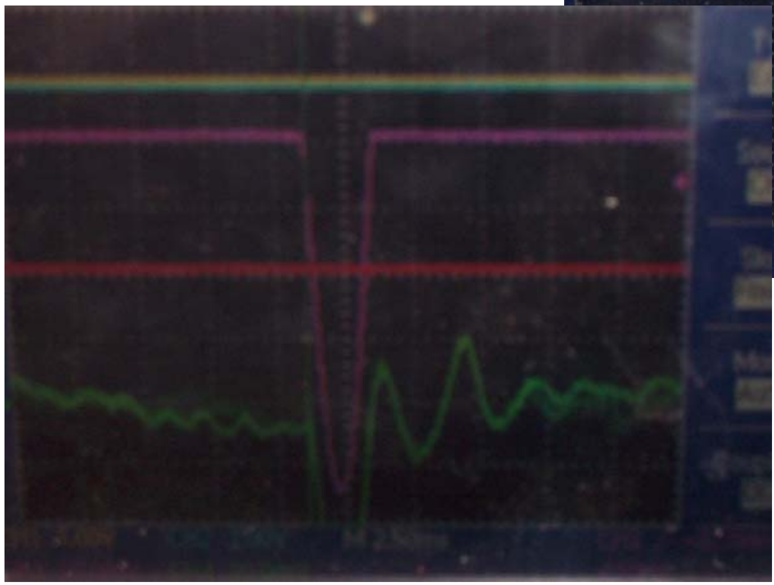
Piezo not connected



Piezo connected but “out-of-phase”: raising oscillations!



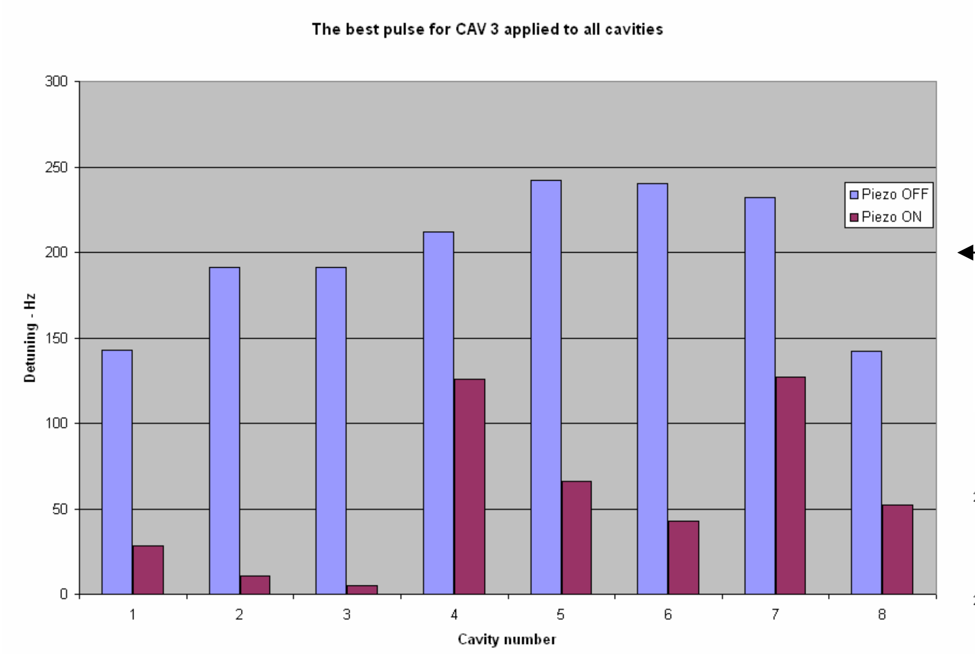
Piezo connected with correct timing: dumping oscillations and compensate detuning



The best pulse for cav3 applied to all cavities

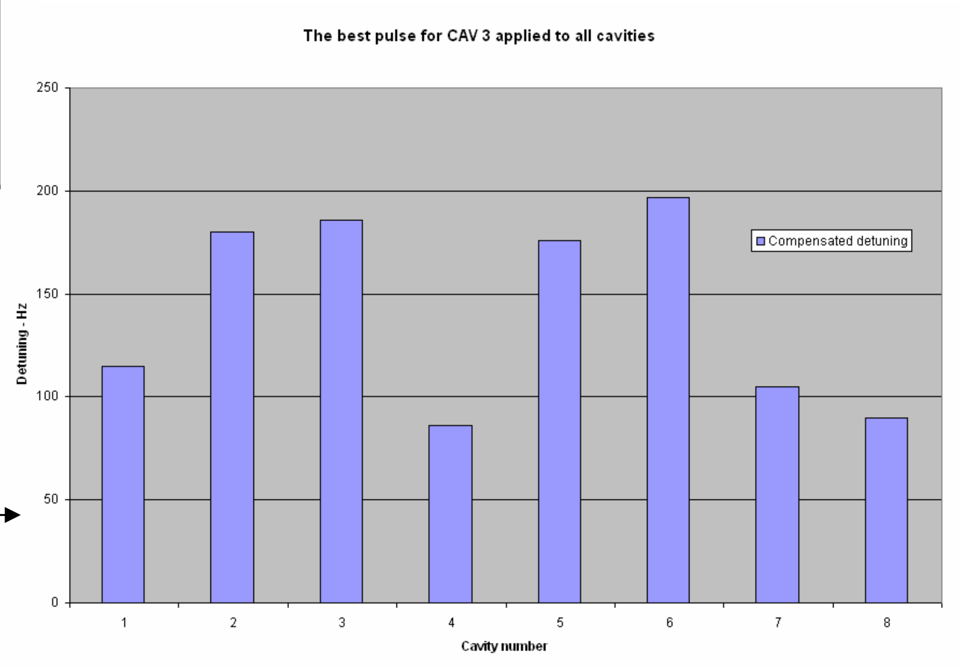
(To save time due to the incoming warm-up dead line) the best piezo pulse found for cavity 3 has been applied to all other cavities, in order also to verify the differences among them.

Though the compensating effect is clear for every cavity, still significant differences are evident.



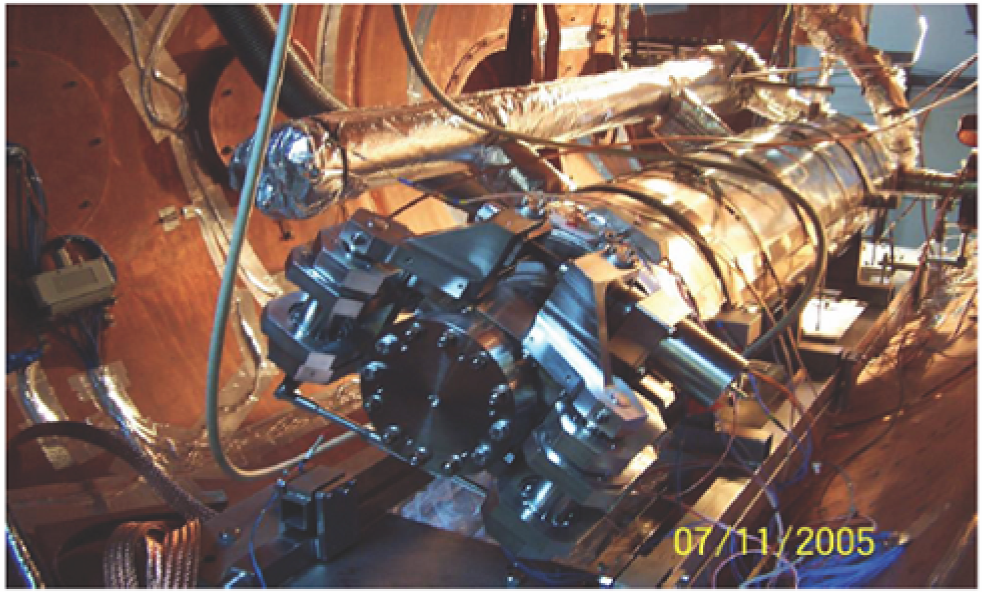
Piezo pulse ON and OFF comparison with the same pulse

Detuning compensated with the same pulse

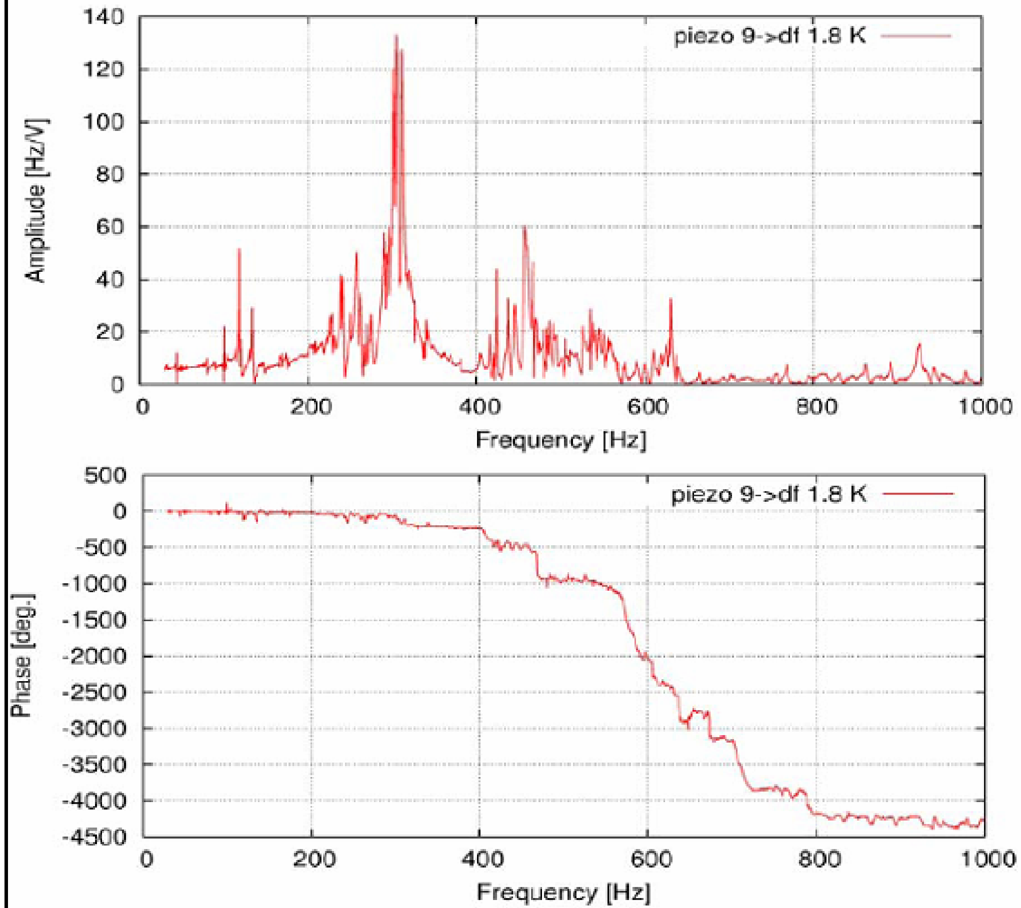


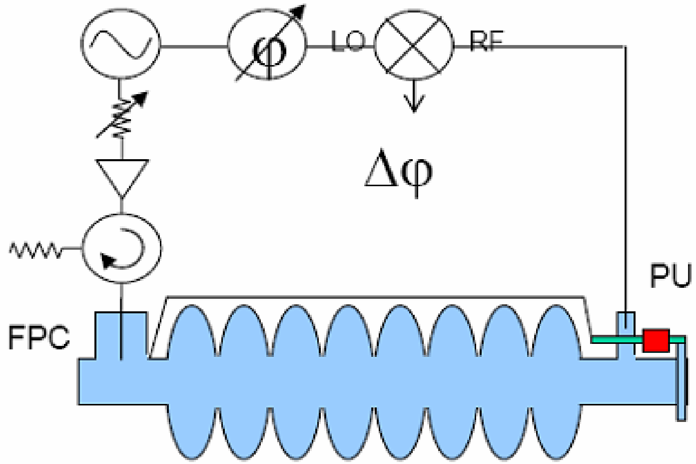
1.8 K Measurements in CryHoLab

- Static range for one piezo :
  - Δf = 800 Hz for a driving voltage of 100 V DC (Not tested at higher voltage)
- The measured temperature of the piezos is between 20 and 30 K
- Slow tuner range : 500 kHz
- Transfer function measurements



1.8 K PZT→Δf transfer function in CryHoLab



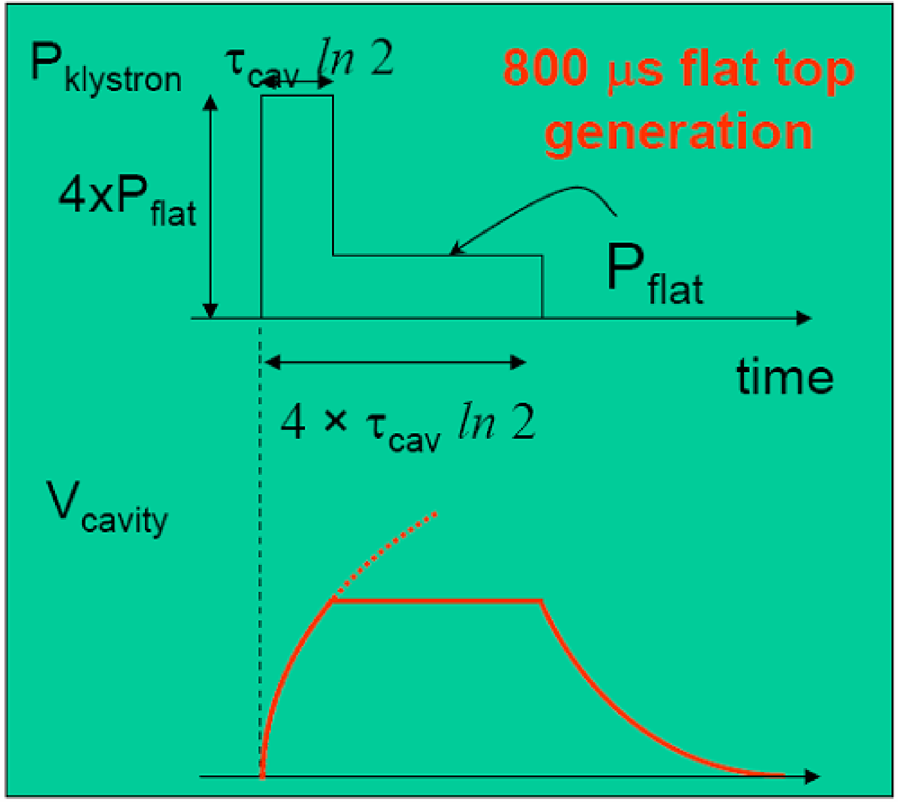


- Piezo to Δf TF : large number of modes. The PTS is likely to couple longitudinal and transverse modes of the cavity

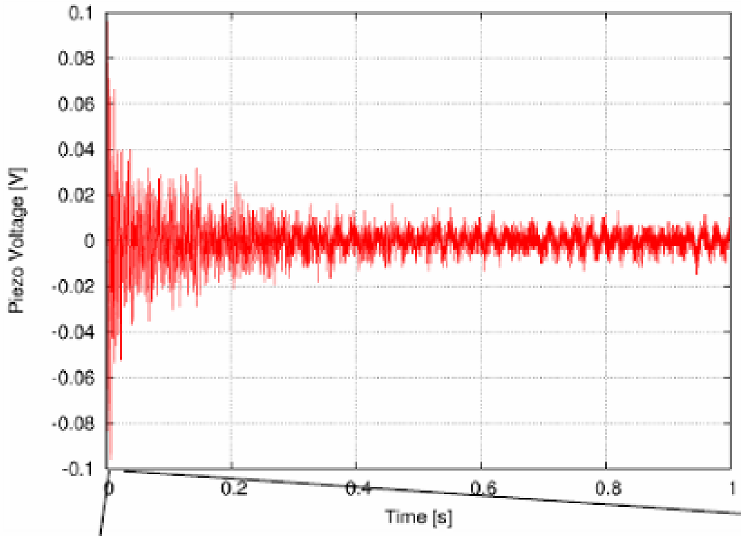
Mechanical delay 400 μs (propagation time in the structure)

1.8 K Pulsed operation in CryHoLab

- RF source : 1.5 MW, 1ms pulse, 6.25 Hz max
- Rep. rate for the LFD experiments is 0.87 Hz
- DESY TTF-III coupler – Measured Q_{ext} = 1.34 10^6
- Maximum E_{acc} = 25 MV/m, limited by field emission on the test cavity (C45)
- RF pulse is different from TTF pulse:
  - Faster rise time = 200 μs instead of 500 μs
  - Same flat top 800 μs

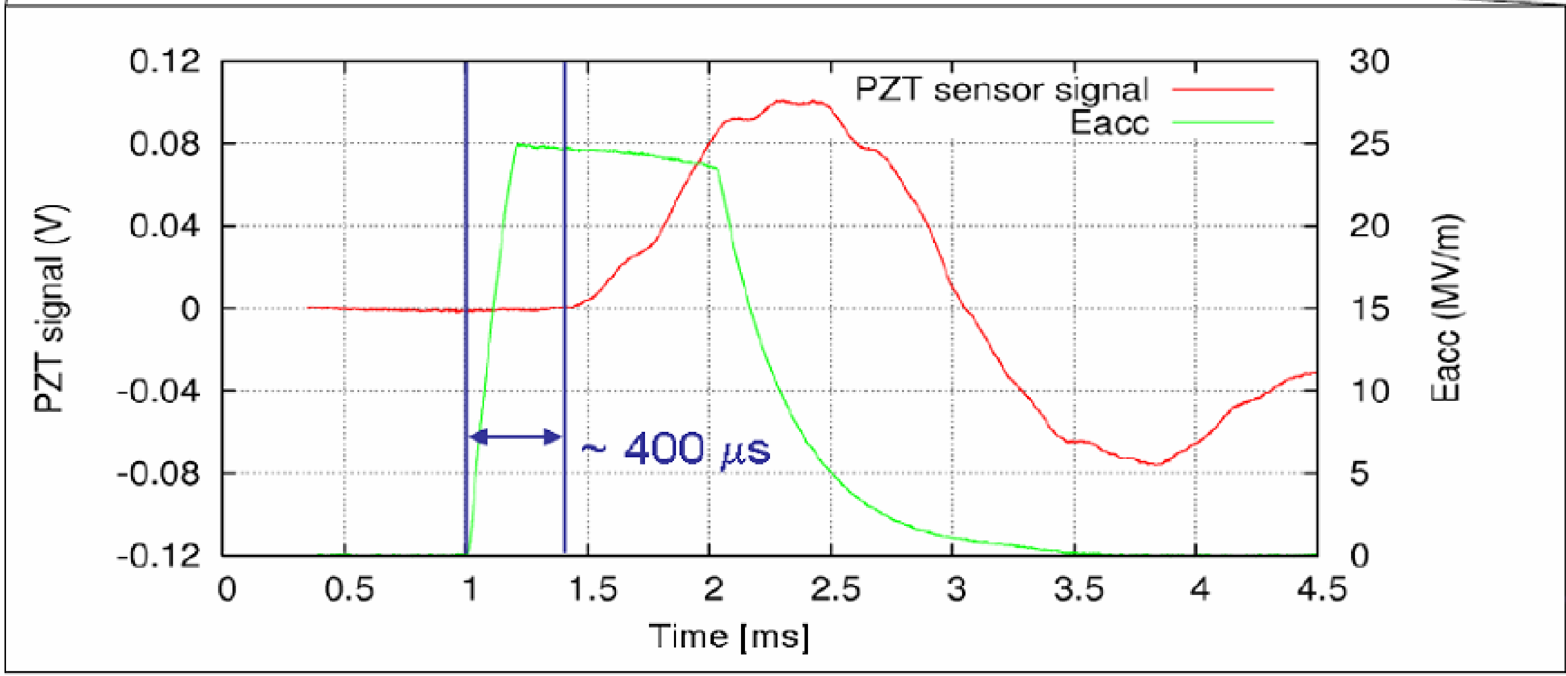


Piezo signal @ 25 MV/m



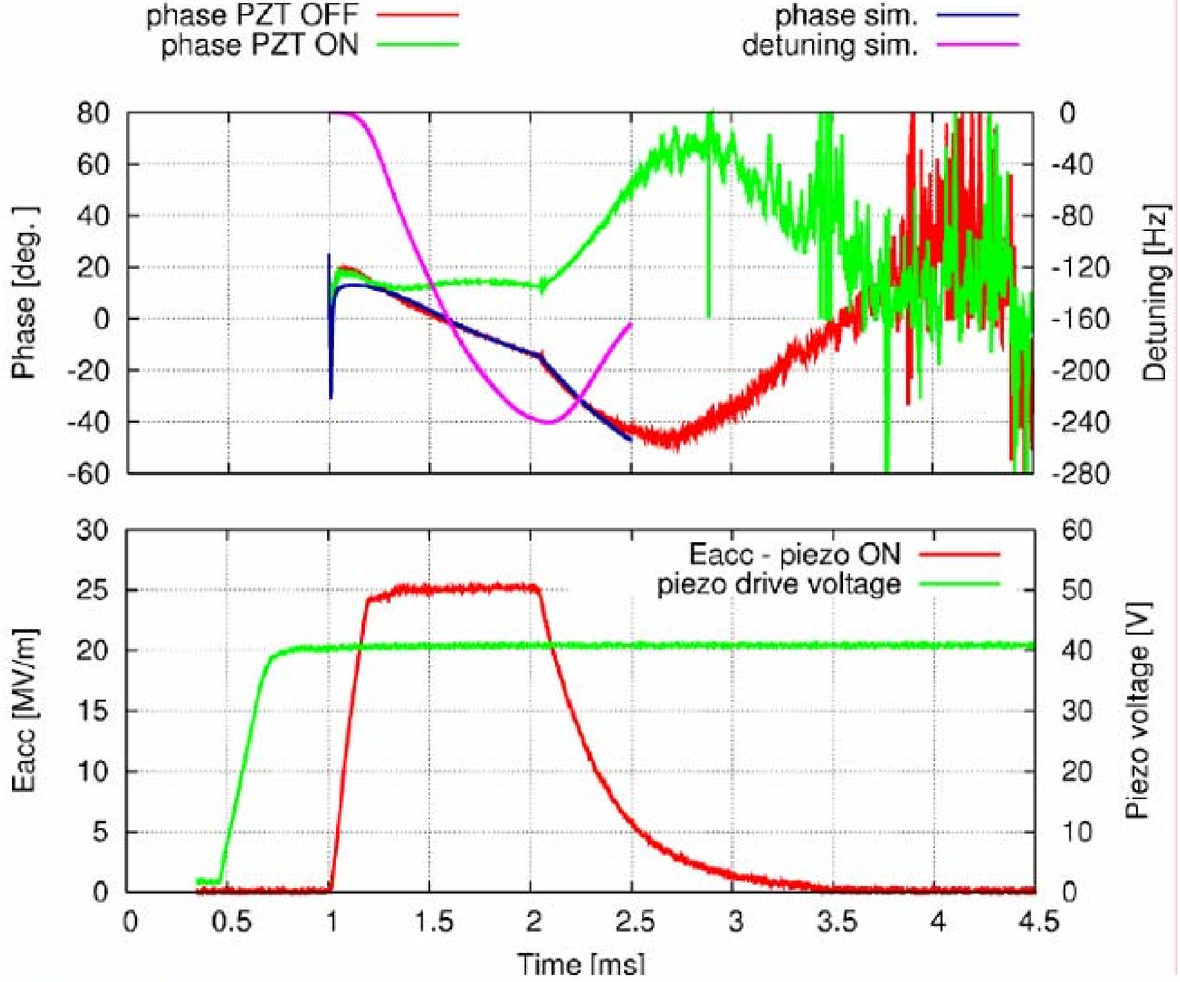
- Piezo signal is the superposition of the response to Lorentz force (≈ impulse response) and to background vibrations (He, pumps,site) which cause microphonics

- Major contribution of LFD through the 306 Hz mode (Qm ≈100)



LFD compensation @ 25 MV/m

- minimize the cavity voltage phase excursion during the flat top
- Parameters for a simple PZT driving pulse: pre-delay, amplitude, rise time



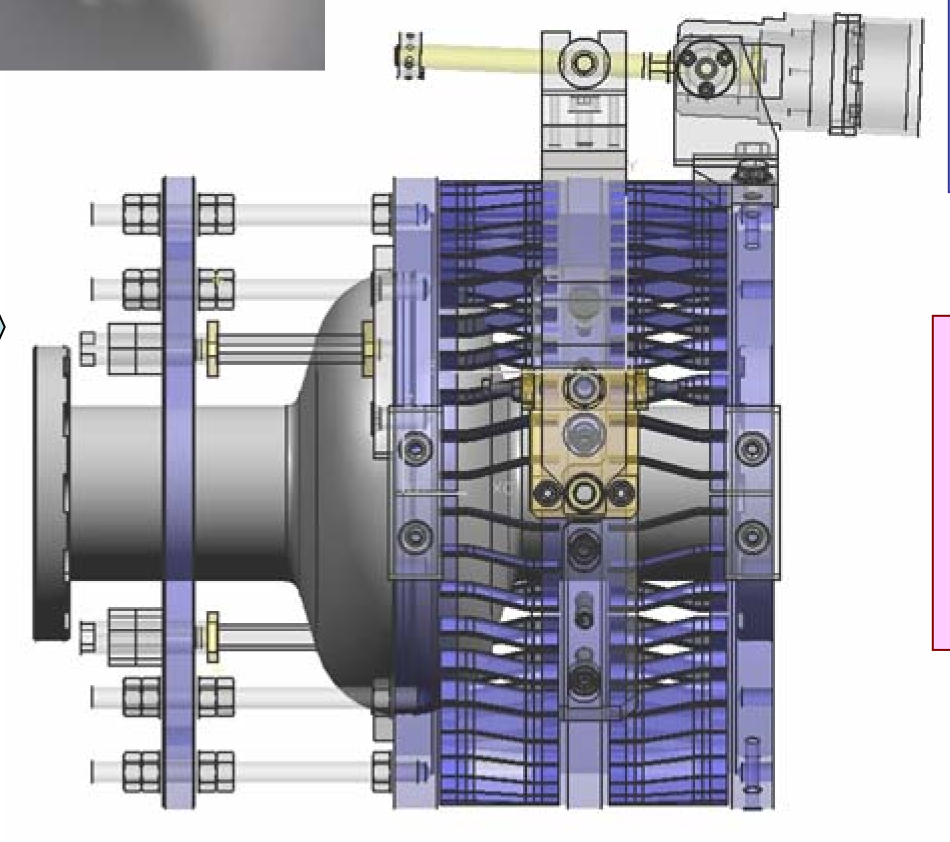
The **detuning of -240 Hz** is derived using a numerical model of the cavity and fitting the measured amplitude and phase.
With compensation the detuning is **reduced to 20 Hz** peak-peak during the flat top.

Summary of tests results

- The collected results of the tests in various labs show that LFD compensation with piezos is possible.
- More than 1 kHz detuning has been corrected with resonant compensation, less with single pulses non resonant modes.
- Other (longer and larger) piezos have to be tested.
- Coaxial blade tuners have still to be tested
- Furthermore the first results in CMTB at DESY seems to be promising. Next test by the end of January with higher voltages and different pulses.
- More work has to be done to optimize piezo-cavity interaction to be more efficient.
- Possibility to compensate microphonics still to be investigated.

Tuner Test Bench

A simple test bench for tuners can be realized using a 1.3 GHz mono-cell cavity, easily upgradable to a real 9-cell cavity.



The cavity dress is designed to accommodate the blade tuner and the piezo actuators, in order that the piezo elements see the stiffness of the true tesla cavity.

The lateral plates can be designed in order to accommodate a proper gasket and allow a cryogenic test of the assembly. This solution can be attained by machining proper groves on the end plates.

Acknowledgements

- Most of the work presented in here is not my own but other people's, as can be seen from the many slides I have borrowed from other presentations.
- So, without listing the names (I surely would forgotten someone) I wish to thank you all these people, especially the ones from:

  - the TTF-TESLA collaboration

  - SRF WP8 (tuner) CARE working package

CARE WP8 Involved Laboratories

DESY - *S. Simrock, L. Lilje, C. Albrecht and Everybody Else not listed here..*
Deutsches Elektronen-Synchrotron

TUL-DMCS - *A. Napieralski, P. Sekalski, M. Grecki & E.E....*
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Technical University of Lodz, Poland

INFN – *A. Bosotti, N. Panzeri, R. Paparella & E.E....*
Italian National Institute for Nuclear Physics, Milan, Italy

IN2P3 – *M.Fouaidy & E.E....*
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Orsay, France

CEA Saclay – *P. Bosland & E.E....*
Commissariat à l'Energie Atomique