WP8.1

Fast Piezo Blade Tuner (UMI Tuner) for SCRF Resonators Design and Fabrication

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Blade Tuner

The design of a coaxial tuner solution was originally motivated from the need of a cold tuner for the TTF superstructures tests. The coaxial blade tuner was then proposed both for the reduced cavity spacing foreseen by the TESLA TDR and for the superstructures, and prototypes without piezo actuators were built and tested in the CHECHIA horizontal cryostat and on the TTF linac in 2002. During both tests the blade tuner performed as expected in terms of stiffness, frequency sensitivity and tuning capability.

Transforms azimuthal rotation in a longitudinal motion

Cinematic description of the fine tuning system
Reference for the new tuner design

The INFN Blade-Tuner

Successfully operated with superstructures
The New INFN Blade-Tuner

- Integration of piezos for Lorentz forces and microphonics completed.
- All the parts have already been constructed by ZANON
- The assembling of two complete prototypes, including the modified helium tank, is well in progress at ZANON
- Two cold tests are preview at DESY and BESSY facilities.
The tuner assembly is mainly composed of three parts:

- the movement leverage
- the bending rings
- The piezo actuators

The piezo actuators provide the fast tuning capabilities needed for Lorentz Force Detuning (LFD) compensation and microphonics stabilization. The design is compatible with other active elements, as magnetostrictive actuators.

The bending system consists of three different rings: one of the external rings is rigidly connected to the helium tank, while the central one is divided in two halves. The rings are connected by thin titanium plates (blades) that, by means of an imposed azimuthally rotation in opposite direction of the two halves of the central ring, can elastically change the cavity length.
How we designed it (1/4)

- Tuner – Cavity – Helium tank system (simple structural model):
  - Axial behavior has been investigated in quasi static conditions
  - Bending behavior has been investigated too
  - The most complicated part is the tuner: axial, bending and shear stiffness have to be considered

Numerical and experimental evaluation of mechanical characteristics of all parts

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Axial stiffness</th>
<th>$c$ (µm/kN)</th>
<th>$k$ (N/µm)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium tank</td>
<td>Ti Gr2</td>
<td>$K_H$</td>
<td>3.30</td>
<td>302.4</td>
<td></td>
</tr>
<tr>
<td>Blade tuner</td>
<td>Ti Gr2</td>
<td>$K_T$</td>
<td>40.0</td>
<td>25</td>
<td>From exp.</td>
</tr>
<tr>
<td>Cavity</td>
<td>Nb</td>
<td>$K_C$</td>
<td>330.8</td>
<td>3.023</td>
<td></td>
</tr>
<tr>
<td>Washer disk</td>
<td>NbTi</td>
<td>$K_W$</td>
<td>71.4</td>
<td>14,001</td>
<td>Both disks</td>
</tr>
<tr>
<td>Piezo actuator</td>
<td>PiC 255</td>
<td>$K_P$</td>
<td>4.76</td>
<td>2x105</td>
<td></td>
</tr>
<tr>
<td>Tuner bellow</td>
<td>Ti Gr1</td>
<td>$K_B$</td>
<td>5263</td>
<td>0.19</td>
<td></td>
</tr>
</tbody>
</table>
How we designed it (2/4)

- The axial behavior of cavity has been predicted.
- The following hypotheses were assumed:
  - mechanical properties at 300 K;
  - quasi-static working conditions, no inertia forces;
  - Helium tank bellow with 7 peaks;
  - Two piezos, 40 mm length, 10x10 mm section

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Frequency Range [kHz]</th>
<th>Axial Movement [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow Tuning</td>
<td>~ 500</td>
<td>~ 1500</td>
</tr>
<tr>
<td>Fast Tuning</td>
<td>~ 1</td>
<td>~ 3</td>
</tr>
</tbody>
</table>

![Schematic diagram]

Due to the low stiffness of the end disks, only 80% of the displacement applied by the tuner is transferred to the cavity. For the fast tuning action a further contribution comes from the tuner stiffness, and 75% of the displacement applied by the piezos is transferred to the cavity. In particular, to provide the values required, the piezo has to assure a maximum stroke of ~ 4 μm at 2 K.

<table>
<thead>
<tr>
<th>Load case: $\delta_T = 1$ mm (slow tuning)</th>
<th>Load case $\delta_p = 1$ μm (fast tuning)</th>
</tr>
</thead>
<tbody>
<tr>
<td>------</td>
<td>----------------</td>
</tr>
<tr>
<td>He + disk</td>
<td>-2435.0</td>
</tr>
<tr>
<td>Tuner</td>
<td>-2622.5</td>
</tr>
<tr>
<td>Cavity</td>
<td>2435.0</td>
</tr>
<tr>
<td>Piezo</td>
<td>-2622.5 / 2</td>
</tr>
<tr>
<td>He bellow</td>
<td>187.5</td>
</tr>
</tbody>
</table>
Two rings are welded to the helium tank. The blade tuner is fixed to one of them by means of twelve bolts, while the other ring can receive up to four piezo actuators. Ad-hoc devices have been designed so that piezos of different section and length up to 72 mm can be accommodated.

- Because the tuner is fixed to the helium tank, a bellow is needed between the two fixed rings. The number of convolution has been computed in order to avoid any non-elastic strain in the bellow for a maximum axial displacement of 1.8 mm.

- The position of pad supports has been reviewed in order to minimize the bending forces on the helium tank bellow and, of course, on piezo elements.

- Four rigid bars have been foreseen between the blade tuner and the ring that receive the piezo actuators in order to stiffen the assembly during transportation. The same bars can be used as safety device in case of piezo damages.
Due to the change of the Helium Tank with the introduction of the bellow, an accurate evaluation of the vertical displacement has been done. The maximum sagging computed (0.12 mm) is less than the admissible tolerance of concentricity of dumb bells (0.6 mm), therefore the new configuration can be accepted with confidence.
<table>
<thead>
<tr>
<th>Guidelines for piezo choice</th>
<th>Blade tuner piezo specifications - Working point, 2K -</th>
<th>Needed properties, for piezo at room temperature</th>
</tr>
</thead>
</table>
| **Blocking force**         | 4 kN closed 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**        | $V_{\text{max}} < 200 \text{ V}$  
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 limit  
No tensile forces  
Vacuum, clean environment |
"Characterized" Piezos

<table>
<thead>
<tr>
<th>PROPERTIES</th>
<th>Unit</th>
<th>Noliac</th>
<th>Noliac</th>
<th>Epcos</th>
<th>PI</th>
<th>Noliac</th>
<th>Piezo mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Room Temperature</strong></td>
<td></td>
<td>SCMA/S1/A/10/10/40/200/60/400</td>
<td>SCMA/S2/A/10/10/42/200/60/4000</td>
<td>LN 01/8002</td>
<td>P-888.90</td>
<td>SCMAS/S1/10/30/200/42/6000</td>
<td>Pst 150/10</td>
</tr>
<tr>
<td>material</td>
<td></td>
<td>medium soft doped PZT-S1</td>
<td>medium soft doped PZT-S2</td>
<td>PZT-nD34</td>
<td>PZT-PIC 255</td>
<td>medium soft doped PZT-S1</td>
<td></td>
</tr>
<tr>
<td>case/preload</td>
<td></td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes / 400N</td>
</tr>
<tr>
<td>length</td>
<td>mm</td>
<td>40 ± 0.5</td>
<td>42 ± 0.5</td>
<td>30</td>
<td>36</td>
<td>30 ± 0.5</td>
<td>64</td>
</tr>
<tr>
<td>cross section</td>
<td>mm²</td>
<td>(10 x 10) ± 0.2</td>
<td>(10 x 10) ± 0.2</td>
<td>6.8 x 6.8</td>
<td>10 x 10</td>
<td>(10 x 10) ± 0.2</td>
<td></td>
</tr>
<tr>
<td>stiffness</td>
<td>kN/µm</td>
<td>0.1125</td>
<td>0.112</td>
<td>0.083</td>
<td>0.105</td>
<td>0.15</td>
<td>0.035</td>
</tr>
<tr>
<td>max. stroke</td>
<td>µm</td>
<td>60 ± 9</td>
<td>60 ± 9</td>
<td>40</td>
<td>35 ± 3.5</td>
<td>42 ± 6.3</td>
<td>80</td>
</tr>
<tr>
<td>blocking force (open loop)</td>
<td>N</td>
<td>4000 ± 800</td>
<td>4000 ± 800</td>
<td>3200</td>
<td>3600 ± 720</td>
<td>4000 ± 800</td>
<td>6000</td>
</tr>
<tr>
<td>blocking force (closed loop)</td>
<td>N</td>
<td>12000</td>
<td>12000</td>
<td>10000</td>
<td>12000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>max. load</td>
<td>N</td>
<td>12000</td>
<td>12000</td>
<td>10000</td>
<td>12000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>res. frequency @ no load</td>
<td>kHZ</td>
<td>38</td>
<td>36</td>
<td>52</td>
<td>40</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>max. voltage</td>
<td>V</td>
<td>200</td>
<td>200</td>
<td>160</td>
<td>120</td>
<td>200</td>
<td>150</td>
</tr>
<tr>
<td>capacity: nominal</td>
<td>µF</td>
<td>8</td>
<td>14</td>
<td>2.1</td>
<td>12.4</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>capacity: measured</td>
<td>µF</td>
<td>8.3</td>
<td>2.5</td>
<td>13.6</td>
<td>6.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Expansion</td>
<td>ppm/K</td>
<td>-2.5</td>
<td>-2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The lifetime of the piezo element depends on preload force!

**The force sensor must guarantee:**
- Direct measure of the **preload** induced by the system on piezoelectric actuators;
- Characterization of actuators in cryogenic environment;
- **In situ** measure of the mechanical stress forces inside the system.

Sensor requirements:
- **High stiffness**: $k \simeq 100$ N/μm
- **Range** = 0 – 2 (5) kN
- **Compact size**: 30 x 30 x 20 mm

**Why do we need a force sensor?**

*Load Buttons could be a good idea!*

**But:** Commercial load buttons, though cheap, of compact size and affordable (at room temperature) don’t work at cryogenic temperatures

**Necessary to prove at LHe temperature**
Construction of a new cryogenic force sensor

Previous measurements have showed an unacceptable behavior of standard load cells when operated in a cryogenic environment.

Results:
Unacceptable lack of stability, uniformity and repeatability in the response

Main problems were:
- **Glue**: plastic deformations appears at low temperature.
- **Strain Gauge**: high virtual load, high hysteresis.

A custom load cell, manufactured by CELMI srl (Buccinasco, Italy), has been realized using strain gauges and glue suitable for cryogenic applications, and tested in order to verify the performances of the cryogenic devoted sensitive elements.

\[ \Delta R = 2R \frac{\Delta l}{l} \]

Strain gauges connected in dual Wheatstone bridge and how they are glued on the load cell membrane.

CELMI load cell mod. 142-500
Cryogenic calibration of the new force sensor

The setup developed for previous load cell test has been used

The test on CELMI prototype has proved that the glue and strain gauge sensors used can work in LHe cryogenic environment with good repeatability and sensitivity. The next step is the realization of a new cell hosting the same sensitive elements but with reduced dimensions.

\[ F[kg] = (25.08 + 49.71 \cdot V_{out}[mV]) \pm 7.5 \text{ kg} \]

CELMI has just realized two prototypes (at cheap price), with reduced dimensions

CELMI load cell mod.142-500 and its support in the vacuum chamber
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. 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 $1.5 \times 10^9$ cycles of switching, up to nearly the maximum stroke, a good estimate of ten years as actuator for ILC cavities.

### Main piezo parameters checked

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity [μF]</td>
<td>13.6</td>
<td>13.6</td>
</tr>
<tr>
<td>Res. Freq [kHz]</td>
<td>45.9</td>
<td>45.2</td>
</tr>
<tr>
<td>Max stroke [μm]</td>
<td>40.2</td>
<td>38.3</td>
</tr>
</tbody>
</table>

### Summary of the test

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>26 Nov 2004</td>
</tr>
<tr>
<td>Stop</td>
<td>20 Dec 2004</td>
</tr>
<tr>
<td>Hours</td>
<td>622</td>
</tr>
<tr>
<td>Cycles</td>
<td>$1.505 \times 10^9$</td>
</tr>
<tr>
<td>Sine Wave Amplitude</td>
<td>$-20V \div +120V$</td>
</tr>
<tr>
<td>Frequency</td>
<td>117 Hz for 4 days, 497 Hz for 6 days, 997 Hz for 16 days</td>
</tr>
<tr>
<td>Average Preload</td>
<td>1.25 kN</td>
</tr>
<tr>
<td>Max Current [rms]</td>
<td>&lt; 200 mA</td>
</tr>
<tr>
<td>Average Temperature</td>
<td>81 K</td>
</tr>
</tbody>
</table>

### Experimental apparatus block diagram

- **PI E-480 Piezo Amplifier**
- **HP Signal Generator**
- **Differential Amplifier**
- **Keithley DMM 199**
- **Keithley 2700 DMM**
- **CLTS out, CLTS piezo**
- **CNX 106, CNX 113**
- **Tektronix Digital Scope**
- **PIRANI Sensor + Display**
- **Box Pressure**
- **Calibrated Force Sensor**
- **Stiffer Steel Rod for Load Transfer**
- **Isolation Vacuum**
- **Piezo Under Test**

### Hysteresis loops comparison

**before test**

**after test**

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*15*
Piezo thermal shrinking measurement

Device for the measurement of the thermal shrinkage

LVDT Transformer cylinder (clamped to the support)
LVDT Magnetic core
Device under test

SM1 LVDT position transducer
Sensitivity@20kHz\(\sigma\) = 149 mV/V/mm

Alternative design
Conclusions

• The coaxial blade tuner prototype construction is in progress;
• Cold tests are preview for the beginning of the next year;
• Many piezos suitable to be employed as fast elements in the tuner have been evaluated;
• Between the ones that met the specifications we have chosen the items with highest stroke for the prototype tests;
• A load cell working at cryogenic temperatures to measure the pre-load on piezo has been constructed. The activity on pre-load detection using the piezo resonant frequency shift method is still in progress;
• Other piezo properties such as thermal shrinkage at cryogenic temperatures or the piezo stroke at LHe temperature with varying dynamic load will be investigated in the next future.