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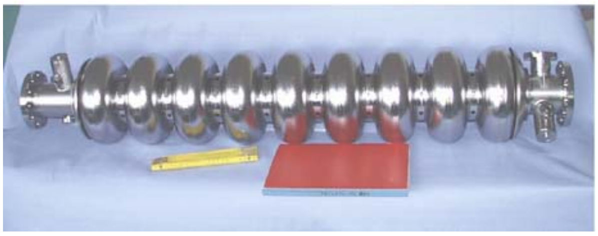

Mechanical study of the « Saclay piezo tuner »
PTS
(Piezo Tuning System)

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Abstract

This report presents the piezo tuner developed at Saclay in the framework of CARE/SRF. We made preliminary estimations of the forces that should be applied on the piezo after cooling the cavity. These rough estimations allowed us to think that it will be possible to tune the cavity at warm in such a way that both the working frequency 1.3 GHz and a good piezo preload shall be simultaneously reached at 2 K. This condition is the basis for a possible development of such a piezo tuner.

Introduction

In the framework of CARE/SRF, the task of CEA Saclay DAPNIA is the design, the fabrication, and the full test in CRYHOLAB of the new piezo tuner for Lorentz force detuning compensation on a TTF cavity.
The present tuner is working inside the TTF cryomodules without any piezo actuator. Thus the Lorentz force detuning in the pulsed mode of the accelerator is limiting the maximum accelerating field of the cavities at about 25MV/m.
Piezo actuators have been integrated in this tuner by the DESY team for tests, and this system demonstrated the compensation of the Lorentz force detuning at field higher than 35 MV/m.
Nevertheless this system is an adaptation of a piezo actuator on a mechanical part which was not initially developed for that. As a consequence this tuner has several defects: its stiffness is too low, it is difficult to adjust the preload applied at cold on the piezo actuator in the good range with a good reproducibility, and only part of the maximum piezo actuator stroke is transmitted to the cavity flange.
Our goal is now to develop a new tuner which should allow obtaining a better preload adjustment and a better efficiency of the stroke transmission. The mechanical studies are now finished, and fabrication is in progress. This report presents the principle of this new system with associated mechanical calculations.

Principle of the PTS

This new system will be mounted on the present cavities without any modifications of the helium tank and cavity flange on which the present TTF tuners are mounted.

As it is shown on figure 1, the PTS is a double lever with a screw-nut system moved by a stepping motor with a gear box. The design is a mixing of the present TTF tuner and of the Super-3HC tuner. This system allows slow tuning of the cavity. On one side one of the levers is fixed on a piezo actuators support which is fixed on the helium tank. Motion made by piezo actuators are transmitted to the cavity flange by the different parts of the tuner.

Less than half of the piezo stroke can be transmitted to the cavity flange if we take into account the geometry of the system and the fact that part of the stroke will be lost in the different interfaces.

It will allow pre-tuning the cavity during the assembling at 300K within ±2 MHz range. At 2K the tuning range will be ± 460 kHz.

The principle of the PTS is based on the fact that the preload is directly applied on the piezo actuators by the cavity elasticity. No additional force is applied by the support of the piezo actuators (except by the weight of the components of course).

2 piezo actuators are inserted in the PTS at symmetric positions that allow interchangeable roles: both piezos can be used as actuator or sensor.

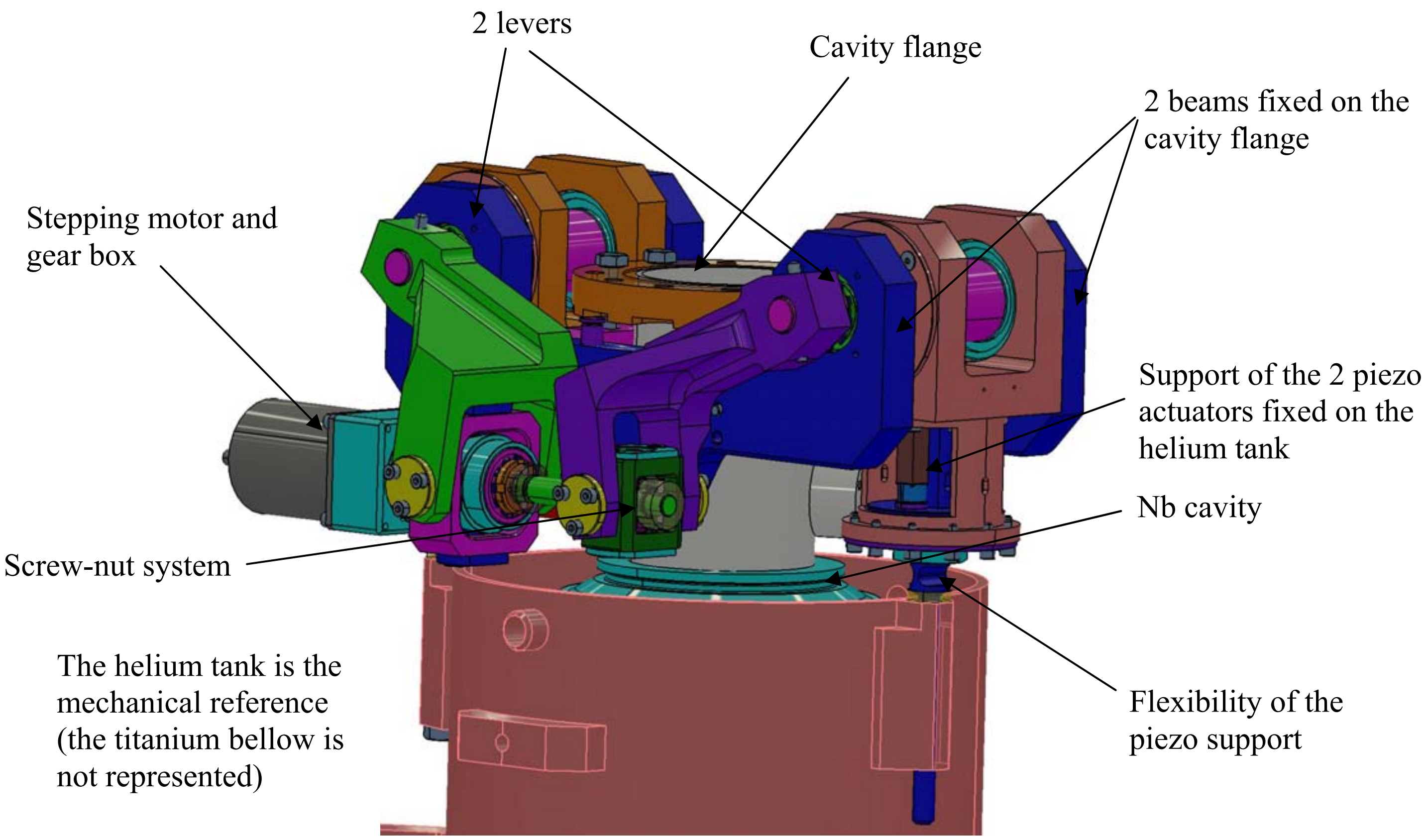

Figure 1: Schematic view of the PTS

Once the cavity is cold, it shall be always stretched in the whole tuning range and never cross the “zero stress point”. The piezo actuator inserted between the cavity flange and the helium tank, i.e. the mechanical reference, is then always compressed by the force of the cavity elasticity.
The compression on each piezo actuator shall be kept lower than its blocking force (between 10% and 50% is a good situation). This blocking force depends on the piezo actuator, and can vary from 3 kN to 6 kN.

Our design is based on the NOLIAC PZ29 actuator (cross section 10x10mm, length 30mm). At room temperature the blocking force is about 6 kN, the stroke is 42 µm at 200 V and their stiffness is 150 kN/mm. Our system will also accept longer actuators, and it will possible to mount P.I. piezos 36 mm long delivered by IPN Orsay, and make test with this second piezo actuators. The blocking force of P.I. piezos is about half of the NOLIAC ones (3 kN), the stroke is 30 µm at room temperature and their stiffness is about 100kN/mm.
The differences in the fabrication process between these 2 piezo types may also lead to differences in the behaviour at cold. 6 NOLIAC piezo actuators have been given to M. Fouaïdy (IPN Orsay) who will perform measurements of the stroke and capacitance as a function of the temperature between 300 K and 4 K, at different loads, before and after irradiation.

The maximum stroke of the piezo actuator will be about 5 µm at 2 K. If this stroke is transmitted to the cavity flange without any loss, only half of it, i.e. 2.5 µm, will be effective on the cavity flange because of the geometry of the system. The corresponding frequency shift is about 1.3 kHz, which is only a little more than the needed value for Lorentz forces compensation at high fields. Thus the goal of our study is to limit the losses of stroke between the piezo actuators and the cavity flange in order to keep a little margin and reach the compensation detuning amplitude needed at high fields.

The stroke losses are of course dependent on the tuner and piezo support design, but also, and mainly, on the cavity tuning process during its preparation.
The piezo support is described in a first part. The cavity preparation sequence is analysed in a second part for the determination of a frequency tuning which should allow reaching simultaneously the nominal frequency 1300 MHz, and the preload applied on the piezo at 2 K.

Piezo actuator support

The piezo support is placed between one of the tuner lever and the helium tank as it is shown on figures 1 and 2. Two piezo actuators will be mounted inside.

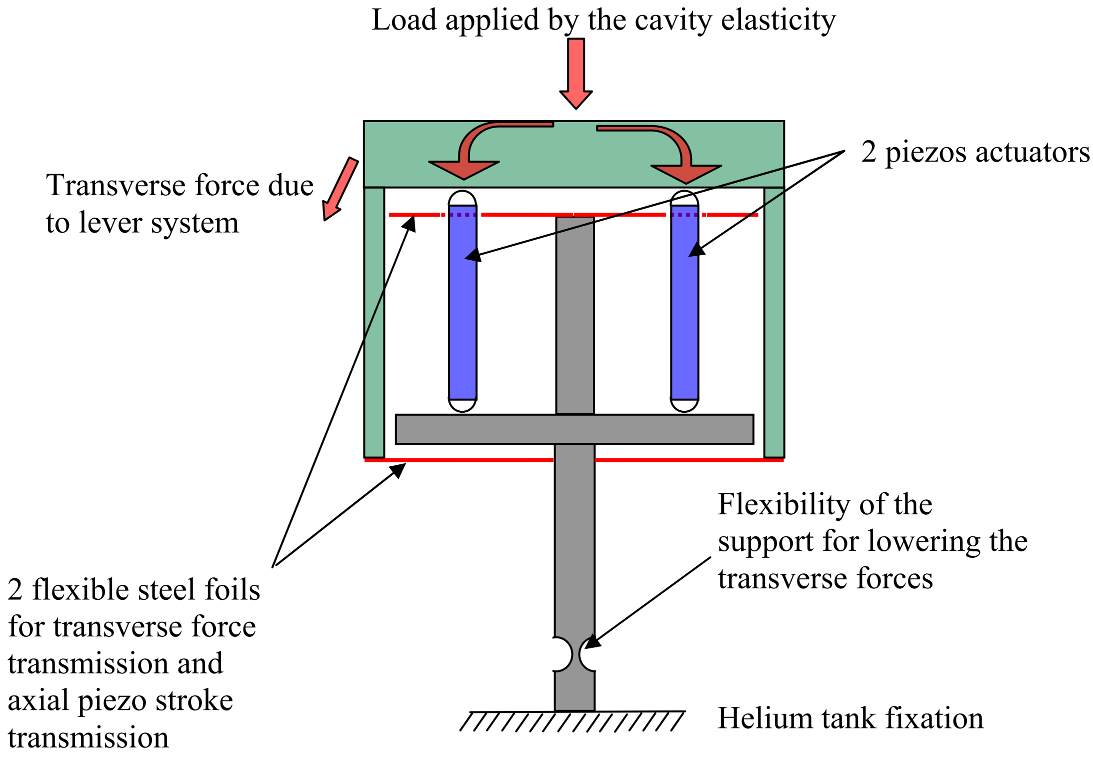

Figure 2: schematic view of the piezo actuators support.

The 2 piezo actuators are guided by 2 flexible steel foils which have 2 functions:

- Allowing the axial stroke of the piezo actuators. Their axial stiffness, 1 kN/mm, is very small, compared to the 300 kN/mm rigidity of the 2 piezo actuators in parallel.
- Compensating the transverse forces. These forces are generated by the lever acted by the stepping motor which transversely move the upper part of the piezo support. The

force is minimised by the flexibility given by machining the lower part of the support fixation on the helium tank (see figure 1). The 2 steel foils transmit this force from the upper part (fixed to the lever system) to lower part of the support (fixed to the helium tank). The piezo actuators being simply guided at their extremities with sphere-cone systems don't see these dangerous transverse forces.

The maximum transverse forces through the foils have been estimated at about 20N.

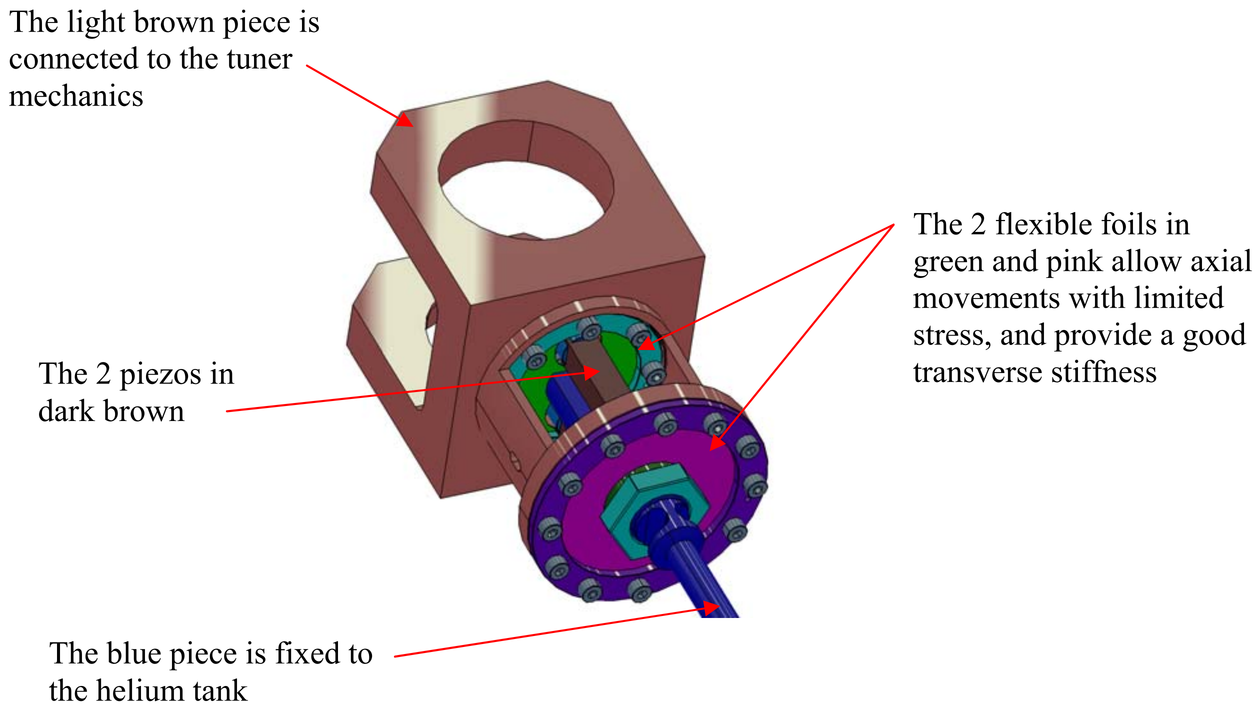

Figure 3: drawing of the piezos support

This guiding system with 2 steel foils was preferred to friction guiding systems which seemed to be less efficient for full stroke transmission because of the very small amplitude.

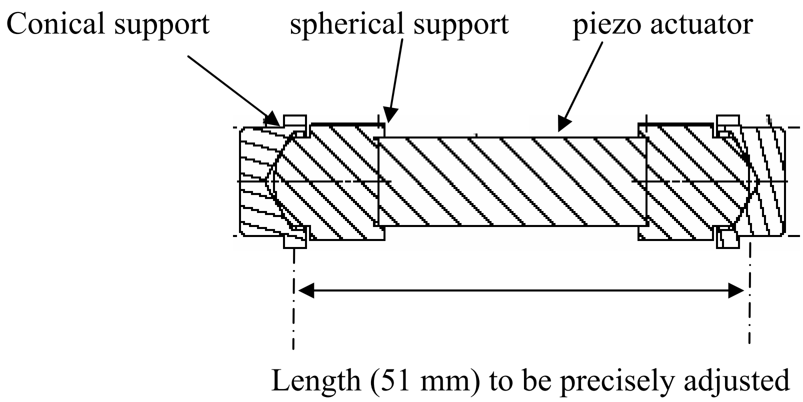

Figure 4: the sphere-cone system

The two piezo actuators are mounted with a sphere-cone system which has been designed in such a way that it will be possible to adjust with the maximum precision the length of each assembly composed of 5 elements: the piezo actuator, the 2 spherical supports glued on the piezo, and 2 conical supports on which the spheres will lean on. Once the two extremity pieces are machined, these 5 elements (see figure 4) will be matched together.

This precaution will allow to:

1. Equilibrate the compression load on the 2 piezos. The piezo actuators are delivered with poor tolerance on their length: ± 0.5 mm. After gluing the two spherical supports the tolerance is even more degraded. Only a final machining can give the necessary precision on the final assembly.
2. Minimise the deformation of the 2 steel foils which are designed to work with small axial amplitude.

Cavity frequency and piezo preload.

As it has already been described in the previous paragraph, the preload is directly applied on the piezos by the cavity elasticity. Thus the elastic deformation of the cavity at cold has to be determined so as to get simultaneously the nominal frequency and a good preload on each piezo.
Because of the thermal shrinkage of the different components cooled down to 2K, the very small acceptable preload range applied to the piezos actuators is difficult to reach with the nominal frequency of the cavity.

The key parameter for obtaining this coincidence is the cavity frequency after field flatness adjustment, and before welding the helium tank. If a cavity is not tuned at the good frequency after welding its helium tank, it will not be possible to get simultaneously the good values for frequency and preload at cold.

This frequency will have to be determined taking into account all effects of the cavity preparation that are made after the tuning: chemical treatment, pumping, etc.

Fortunately the number of cavities that have already been prepared at DESY gives now good statistics, and this process is now precisely determined for the present configuration with the tuner without piezo.
Nevertheless the process will have to be modified because unlike the present tuner which compresses the cavity, the new piezo tuner will stretch it.
Determination of the optimum tuning frequency will be made experimentally with a PTS mounted on a TTF cavity after several cooling down, warming up, dismounting and remounting. However for the mechanical study, and also for the first tests at cold, we need estimation of the tuning frequency and of the piezo preload values. This preliminary (rough) analysis of the system is described bellow.

Cavity frequency during preparation process:

Before calculating the forces applied by the cavity, one has to analyse the cavity preparation process, and its effects on the cavity detuning which will need to be compensated by a deformation. The scattering effects of the preparation reported by the DESY team (private communication by Guennadi Kreps) are taken into account by adding a minimum correction corresponding of half of its random detuning effect.

Let's first look at the frequency shifts during the cavity preparation process, and their scattering values.

1. Cavity as received:
   a first chemical treatment is made to remove about 120 µm of niobium.

2. field flatness and cavity tuning:

after the first big chemical treatment the cavity shall be tuned and the field flatness be made at the frequency

$$F_1 + \Delta F_1$$

F_1 value is the key parameter to be adjusted in order to obtain the good frequency and the good preload at 2 K.

We think it is possible to obtain $\Delta F_1 = \pm 2$ kHz, which is the minimum value limited by RF measurement scattering at room temperature.
At this time the cavity is opened at air.

3. 20µm chemical treatment for RF surface preparation:

$$F_2 = F_1 - 200 \text{ kHz} \pm \Delta F_2$$

Chemical effect scattering observed by DESY: $\Delta F_2 = \pm 50$ kHz

4. Pumping the cavity vacuum:

$$F_3 = F_2 + 375 \text{ kHz} + \Delta F_3$$

Pumping effect scattering observed by DESY: $\Delta F_3 = \pm 15$ kHz

5. Full cavity assembling with power coupler and tuner – pre-tuning before cooling:

$$F_4 + \Delta F_4$$

RF measurement scattering: $\Delta F_4 = \Delta F_1 = \pm 2$ kHz

- The cavity is pumped, and the helium tank at atmospheric pressure
- F_4 is the second main parameter to be adjusted

6. Cooling down to 2K:

$$F_5 = F_4 + 2.00 \text{ MHz} \div 2.09 \text{ MHz}$$

cooling effect scattering observed by DESY: $\Delta F_5 = \pm 45$ kHz
(Including the pressure effect of pumping on the helium bath from 4.2K to 2K: - 40 kHz.)

7. Final tuning to F_0= 1300MHz:

F_5 can be chosen different from F_0 in order to avoid plastic deformation during cool down, or to avoid some stress states that can damage the piezos.

$$F_0 = F_5 + \Delta F_0$$

ΔF_0 is not a scattering value, but the final tuning at cold made by the stepping motor of the tuner.

Piezo actuators preload

The force applied by the cavity elasticity on the piezos actuators is determined by 5 parameters:

- the thermal shrinking of the different components: the niobium cavity and the helium tank titanium and stainless steel of the tuner
- the tuning before cooling at frequency F_4 (see next paragraph)
- the different scattering effects during the cavity preparation..
- cavity deformation during the tuning with the stepping motor
- the frequency F_1 after field flatness adjustment, which fixes the cavity neutral point

Calculation of the cavity elasticity and of the cavity frequency to deformation gives the following values:

- tuning sensitivity: 530 kHz/mm
- cavity elasticity: 3217 N/mm
- cavity elastic limit: ± 1.4 mm (at T=300K the Nb elastic limit is 40 MPa)

1. *Force due to cooling:*

The linear thermal contraction at 2 K relative to 300 K, of the cavity niobium, the titanium helium tank, and the tuner stainless steel, are the following:

- $\Delta L/L$ (Nb) = 1.43 10^{-3}
- $\Delta L/L$ (Ti) = 1.51 10^{-3} > $\Delta L/L$ (Nb)
- $\Delta L/L$ (SS) = 3.06 10^{-3} > $\Delta L/L$ (Nb)

The coefficient for piezo actuators is not yet known. For the following calculation we took 0.56 10^{-3} which is the value for pyrex. The corresponding thermal contraction from 300K and 2 K of a 30 mm long piezo actuator is about 0.017 mm.

The results of calculations taking into account the stiffness of the helium tank give an estimation of the force applied by the cavity which extends the tuner:

Δf_{cool} = 676 N on the cavity flanges

The force corresponding to the piezo (pyrex) contraction is about 55N, which is about 8% of the total force. This is not negligible, and that demonstrate the importance of determining the thermal contraction of the piezo actuators.

Thus taking the total force of 676 N, the thermal shrinking decreases the force applied on each piezo actuator by about

Δf_{cool} = - 148 N on each piezo actuator

2. *Scattering effects:*

We have to take into account some scattering effects of the cavity preparation on its frequency in order to avoid crossing the cavity neutral point, and stretching the piezo actuators.
The uncertainty on the frequency value at 2K is, in the worst case, the sum of the scattering effects (excluding ΔF_4 pre tuning):

$$\Delta F = 2 + 50 + 15 + 45 = \pm 112 \text{ kHz}$$

This error on the frequency at cold shall be corrected by acting the stepping motor of the tuner and deforming the cavity. The resulting preload on the piezos will be modified by the elasticity of the cavity.
The uncertainty on the forces applied by the cavity corresponding to the frequency uncertainty is about:

$$\Delta f = 3217 * 112 / 530 = \pm 690 \text{ N}$$

The corresponding safety margin can be taken by increasing the preload and stretching the cavity by: $\Delta l_{cav} \approx 690 / 3217 = 0.214$mm

3. *Preload changes due to the cavity tuning:*

The full tuning range available is about ± 460 kHz. The corresponding forces range applied by the cavity is:

$$\Delta f_{tun} = 3217 * 460 / 530 = \pm 2815 \text{ N}$$

It is then necessary to analyse the possibility to get a compression force higher than zero on the piezo when the tuner is acted to the extremity of the tuning range in the direction of the cavity compression.

4. *Minimum preload force:*

At 300K and just before cooling, the minimum force that has to be applied by the cavity on the piezo actuators, in order to keep them in a compressed state at 2K is defined by the sum of the different effects previously listed: thermal compression, scattering, and tuning effects

$$F_{min} = 676 + 690 + 2815 = 4180 \text{ N}$$

This force corresponds to a cavity elongation reference to its neutral point at 300 K of $\Delta l_{cav} \approx 1.3$ mm. Stretching the cavity of 1.3 mm allows to keep a compression force higher than zero, in the worst case and at the extremity of the tuning range in the direction of the cavity compression.

This value is close to the cavity elastic limit, 1.4 mm. It is thus possible to take some more margins from the neutral point, and compress a little more the piezos by stretching the cavity by:

$$\Delta l_{cav} \approx 1.4 \text{ mm}$$

Taking this value, the force applied by the cavity on the piezos shall be kept between F_{min} and F_{max}, with:

$F_{min} = (1.4 - 1.3) * 3217 = 322$ N
$F_{max} = 322 + 2*690 + 2*2815 = 7330$ N

Thus if we take into account the full tuning range of the tuner, the preload on each piezo should be kept in the range:

$$70 \text{ N} < F_{preload} < 1610 \text{ N}$$

In the worst case a compression force of 70 N is applied on the piezo actuators, which is a very small value. However the experience on the present TTF cavity preparation shows that the full tuning range is never used. Thus, it seems reasonable to think that after several cavity preparations; only small amplitude will be needed to tune the cavity at the nominal frequency at cold. This would allow keeping the preload forces close to the middle of the calculated range, 840 N, which is an acceptable value for the NOLIAC piezo actuators.

For piezo actuators which have lower optimum preload values, it shall be necessary to determine other preparation conditions in order to avoid negatives or too high preload forces. Experiences with such low preload piezos shall be made in a second step, after first tests with piezos accepting larger forces range.

Estimation of the cavity frequency tuning:

When it is opened to atmospheric pressure, the cavity shall be at its neutral point, and its frequency is F_2 (after 20 µm chemical treatment)

When cavity is pumped, outside and helium tank at atmospheric pressure, the neutral point corresponds to the frequency: F_3 (the pressure effect on the cavity extremity flanges -30 kHz is neglected in a first step)

Estimated values of F_1 and F_4 can be then calculated for keeping the piezo actuators in a good preload range:

$$F_5 = 1300 \text{ MHz} = F_1 \underbrace{- 0.2}_{\text{Chemical treatment}} + \underbrace{0.375}_{\text{pumping}} + \underbrace{0.742}_{\text{cavity stretching}} + \underbrace{2.045 \text{ MHz}}_{\text{cool down}}$$

$$F_4 = F_1 \underbrace{- 0.2}_{\text{Chemical treatment}} + \underbrace{0.375}_{\text{pumping}} + \underbrace{0.530*1.4}_{\text{cavity stretching}}$$

The estimation of the tuning frequencies F_1 and F_4 which should allow reaching simultaneously the good frequency and good preload at 2 K are:

$$F_1 = 1297.038 \text{ MHz}$$
$$F_4 = 1297.955 \text{ MHz}$$

For comparison the present TTF cavities are tuned at F_1 = 1298.1 MHz for reaching the frequency 1300.260 MHz after cooling down to 2K. Once the cavity at cold, the tuner is acted in order to compress the cavity and tune it down to 1300 MHz.

As we have written above, these values are only estimations needed for first tests at cold, and F_1 frequency should be precisely determined by experience.

Future plan:

Two PTS are being fabricated and will be delivered at the end of May 2005. In the meantime the control system is being made for the stepping motor and for the piezos, allowing cavity vibration and Lorentz forces compensation analysis. Preliminary tests of the tuner will be made on a test stand and also on a cavity at 300K. Final tests at 2 K with a TTF cavity equipped with a PTS and a power coupler are scheduled in CRYHOLAB in September 2005.
These tests will be performed with a TTF cavity tuned at a frequency optimised for the present TTF tuner, and for the new piezo tuner. Thus the working frequency at 2 K will not be 1300MHz, but another value that has to be optimised for the piezo preload, but that is estimated at about 1 MHz above the nominal frequency.

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