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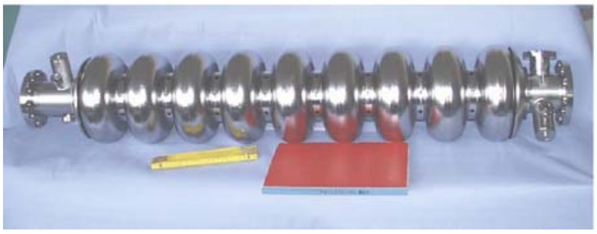

THE FAST PIEZO-BLADE TUNER FOR SCRF RESONATORS

C. Pagani, A. Bosotti, P. Michelato, N. Panzeri, R. Paparella, P. Pierini
INFN Milano LASA

Abstract

The blade tuner concept has been extended to provide the fast tuning capabilities needed for Lorentz Force Detuning (LFD) compensation and microphonics stabilization of superconducting RF cavities. This functionality is achieved in addition to the slow tuning capabilities, extensively proven with the successful experimental program on the superstructures at TTF. Two complete fast/slow tuning systems are being developed in the context of CARE subprograms, one for the high-end ILC case, currently under fabrication, and one for reduced beta elliptical cavities for high intensity pulsed proton injectors.

Contribution to the SRF 2005, Ithaca, New York, USA

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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1 INTRODUCTION

In the ILC project an accelerating field of 35 MV/m and a filling factor higher than that of the TTF are expected. Unfortunately a such high accelerating field require a suitable solution in order to reduce the Lorentz forces detuning.

It has been proven that a piezoelectric tuner system will permit efficient cavity operation at the gradient of 35MV/m [1] but the design requirements are very tight due to the particular working conditions (cryogenic temperature) and to the need to increase the filling factor. For this reason we developed a coaxial tuner solution (blade tuner) inspired by the idea described in [2] and two prototypes were built and tested in CHECHIA horizontal cryostat and on the so called superstructure in 2002 [3]. During both tests the blade tuner performed as expected in terms of stiffness, frequency sensitivity and tuning capabilities.

Later on in order to compensate the Lorentz forces detuning foreseen at 35 MV/m, fast elements have been integrated in the blade tuner and the designed configuration is presented in this paper. The compatibility of the proposed solution with the TESLA/ILC cavities has been proved by means of FE analysis while two complete systems are under fabrication for experimental tests. Its main characteristics are no additional longitudinal space required, usability with minor modification with every SC cavity and possible use of different piezoelectric or magnetostrictive actuators.

2 DESIGN REQUIREMENTS

In the designing of the tuning device it has to be considered that the static Lorentz force detuning strongly depends from the global stiffness of the cavity. As shown in [4], increasing the boundary stiffness will decrease the static Lorentz force detuning and increase the global stability and strength of the cavity. Moreover in [5] it is shown that an eventual interaction between the cavity natural frequencies and the RF repetition rate could lead to an increase of the Lorentz forces detuning effect. For these reasons the end dishes, helium tank and tuner system have to be as stiffer as possible, but such as to avoid the RF repetition rate.

In the case of the TESLA cavities the following parameters have been considered:

- bandwidth: 434 Hz
- cavity sensitivity to axial stretch: 404 kHz/mm

In order to fulfill the tunability requirements of the TESLA project and on the bases of currents warm-cold frequency reproducibility test at the TTF, the values reported in table 1 have been taken into consideration as minimum frequency shift that the tuner must be capable to impose to the cavity.

Table 1: Guidelines for a TESLA cavity tuner.

	Frequency range [kHz]	Axial movement [μm]
Slow tuning	~ 500	~ 1500
Fast tuning	~ 1	~ 3

3 TUNER DESIGN

The tuning system is made of the blade tuner, driven by a stepping motor which provides the slow tuning capabilities, and a fast part that provides the Lorentz forces compensation. In the present design the fast part can accommodates two piezos of different length (from 36 to 72 mm) but if necessary they can be substituted with magneto-strictive elements.

3.1 The blade tuner for the slow tuning

The main tuner mechanism consists of a three-ring bending system connected by welded blades at an angle which transforms the azimuthal rotation (in opposite directions) of the two halves of the central ring into a variation of the distance between the end rings. The azimuthal rotation is provided by a leverage system connected to a stepping motor (see figure 1). The leverage system amplifies the torque of the stepping motor, contemporarily increasing the tuning sensitivity. The maximum axial displacement foreseen for the blade tuner is w = ±1.5 mm.

In the standard design (reported in [2]) the two end rings are rigidly connected to the He tank, which has been split in two halves joined by a bellow in order to allow the variation of the cavity length.

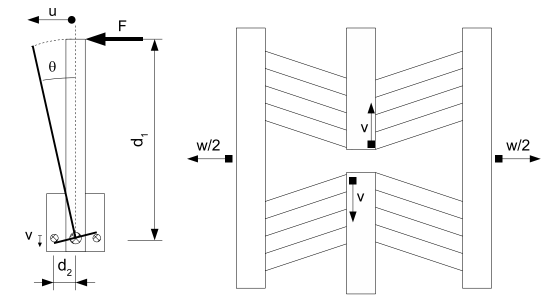


Figure 1: cinematic description of the tuning system

The ring-blade system has been designed with a parametrical model in order to define the structure kinematics and to provide the axial stiffness and tuning force compatibility. The total stiffness matrix obtained by finite element analyses is here reported, while the symbol used are described in figure 2.

$$\begin{Bmatrix} u_{LC} \\ w_{LR} \\ \psi_{LC} \end{Bmatrix} = 10^{-6} \begin{bmatrix} +48.473 & -1.8072 & +0.3349 \\ -3.6144 & +312.27 & +18.422 \\ +0.1675 & +4.6056 & +0.2791 \end{bmatrix} \begin{Bmatrix} Fx \\ Fz \\ Mz \end{Bmatrix}$$

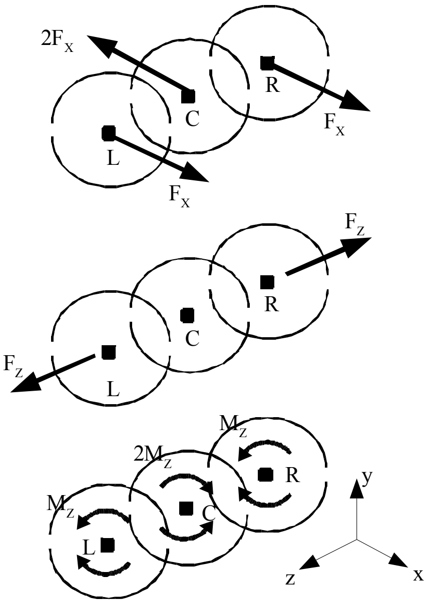


Figure 2: symbol used in the tuner stiffness matrix

3.2 Integration of fast elements

The detailed information obtained by the finite element analysis of the blade tuner has then been used for the integration of a fast tuning action based on piezoelectric actuators, which are subject to several requirements limiting the choice of possible design configurations.

First of all, the piezoelectric actuators (piezos) cannot be subject to tension forces, and bending and shear actions need to be carefully avoided. Moreover, in order to maximize their lifetime, a correct preload range needs to be guaranteed under all operating condition. In addition to that, the characteristic behavior of piezo operation at cryogenic temperatures, in terms of stroke and preload effects, is still a subject undergoing a systematic investigation, especially within the CARE program [6].

From all the considerations expressed above, and using as guidelines the typical values of the TESLA type structures in terms of cavity elasticity and tuning requirements (see table 1), we have integrated the piezoelectric elements in the tuner design, by inserting two elements between one of the end rings and the corresponding flange on the He vessel, as shown in figure 3. The position of the piezo actuators has been carefully chosen in order to avoid possible stresses due to the deflection and vibration of the helium tank. Moreover four bars have been introduced in the design: they can be used both for transportation and safety means in case of piezo breakdown.

The active elements are kept in position by means of supports shown in figure 4: they can accommodate elements of length up to 72 mm and a spherical head is used in order to minimize shear and bending forces.

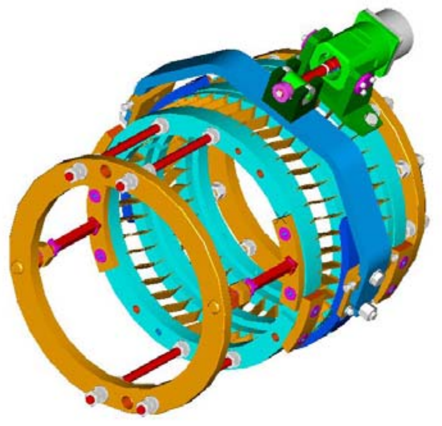


Figure 3: the piezo assisted tuner

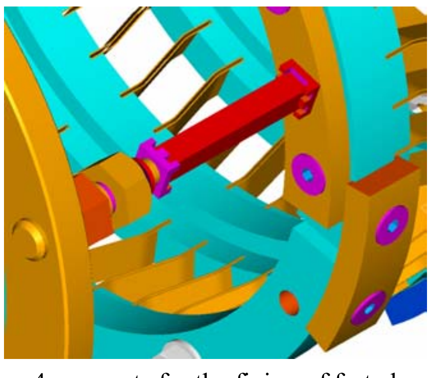


Figure 4: supports for the fixing of fast elements

3.3 Characterization of the full system

The axial mechanical behavior of the full system (cavity + He tank + tuner) has been investigated parametrically by means of the spring model shown in figure 5. The stiffness of every part, for the TESLA cavity case, is reported in table 2, together with the material types, the elastic properties (Young module) and the legend of symbols used in figure 5. The stiffness values were either derived from FEM analysis or measured experimentally [3].

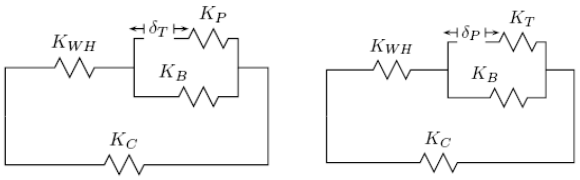


Figure 5: Equivalent spring models

The forces and displacements of every part in the system corresponding to a tuner displacement (δ_T) of 1 mm (slow tuning action) or a piezo displacement (δ_p) of 1 µm (fast tuning action) have been evaluated and are reported in table 3.

Table 2: Characteristics used in the spring model.

Part	Material	Stiffness symbol	E (MPa)	K (N/µm)
He tank	Ti	K_H	105000	302.4
Tuner	Ti	K_T	105000	25
Cavity	Nb	K_C	102700	3.023
End dishes and lips	NbTi	K_W	62055	14.0
Piezo	PIC 255	K_P	45000	2 x 105
Tank bellow	Ti	K_B	105000	0.19

We note here that due to the low stiffness of the end dishes and lips, 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 only 74 % of the displacement applied by the piezos is transferred to the cavity. In particular, to provide the values reported in table 1, the piezos have to assure a maximum stroke of ~ 4 µm at 2 K. The use of stiffer lips for the He tank connection would slightly reduce the requirements on tuner/piezo excursion.

It is also important to point out that the piezo preload is varying with the slow tuner action, therefore a suitable pre-tuning strategy needs to be assessed to ensure that during the slow tuning phase the preload remains within valid operation limits. Furthermore, we have to be sure that the piezo dynamic load is always lower than its blocking force (the force above which the piezo do not provide stroke). For the prototype case of two piezos, with a cross section of 10 x 10 mm, a blocking force of 4 kN (each) is expected therefore if we assume a load limit of 8 kN (obtained subtracting the 4 kN blocking force from the 12 kN nominal load limit) a maximum slow tuning action of ~ 1600 kHz can be safely applied, which is at least a factor of four higher than the current warm-cold frequency reproducibility at the TTF. For sake of safety a lower preload value is preferable.. The experimental tests planned in the context of the CARE program to assess the thermal expansion of different piezo-ceramic materials together with the cold tests of the tuner prototypes (see below for details), will further reduce the overall uncertainty of the preload at the tuner working point. Moreover, the needed cold tuning action is expected to further reduce for the case of a big industrial cavity production, like the one needed by the XFEL or ILC cases.

Table 3: Axial forces and displacements for a tuner elongation of 1 mm (slow tuning action) and for a piezo elongation of 1 µm (fast tuning action).

Load case: δ_T = 1 mm (slow tuning)		
Part	Axial force (N)	Axial displ. (mm)
He + dishes	-2435.1	-0.182
Tuner	-2622.7	1.000
Cavity	2435.1	0.805
Piezo	-2622.7 / 2	-0.013
He bellow	187.6	0.987
Load case δ_P = 1 µm (fast tuning)		
Part	Axial force (N)	Axial displ. (µm)
He + dishes	-2229.1	-0.167
Tuner	-2400.9	-0.096
Cavity	2229.1	0.737
Piezo	-2400.9	1.000
He bellow	171.7	0.904

4 COMPATIBILITY

Compatibility of the presented solution with the TTF design has been checked in terms of transverse displacements (due to the gravity load) and mechanical eigenmodes.

4.1 Bending analysis

A bending analysis has been performed in order to check the vertical displacements of the cavity subject to its weight and to the weight of the tuner. This analysis is necessary because of the modification introduced in the helium tank design.

We point out that, in order to reduce the displacements, the pads at the coupler side (on the right in figure 6) have been shifted by 150 mm towards to the tuner position.

An axisymmetric model with non axisymmetric load has been implemented: it consists of 1713 2-nodes SHELL elements, 539 4-nodes PLANE elements and a total of 2369 nodes (see figure 6), it accounts for the gravity load and neglects any vibration or external perturbation. In this configuration the tuner is considered only as a load and the stiffener effects due to the four safety bars are not considered. The total weight (cavity plus helium tank and piezo blade tuner) is of 598 N and the maximum vertical displacement of the cavity is of 0.144 mm in the up direction at the right end. Because the central lowering is of 0.115 mm (see figure 7) the maximum sagging of the cavity respect to its ends is of 0.115 + 0.144 = 0.259 mm, smaller than the specifications required for the fabrication tolerances of the cells (0.6 mm). The most important displacements are reported in Table 4.

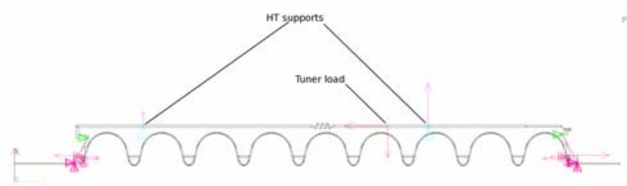


Figure 6: FE model for the analysis of displacements

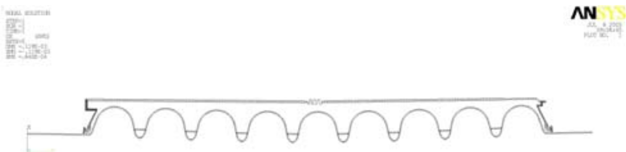


Figure 7: vertical displacements (dead loads)

Table 4: vertical displacements

Position	Helium tank displ. (mm)	Cavity displ. (mm)
Left end	+0.027	+0.063
Center	-0.074	-0.115
Right end	+0.100	+0.144
Sagging	-0.127	-0.259

Neglecting the stress concentrations near the welding point, that are not accurately meshed, the maximum stress in the bellow is equal to 6.3 MPa, lower than the admissible stress (see figure 8).

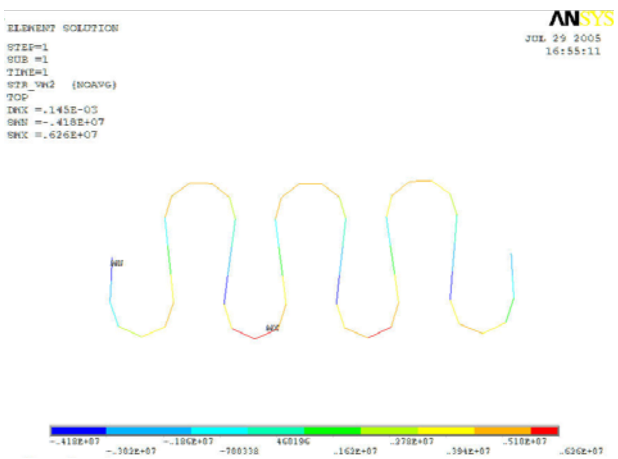
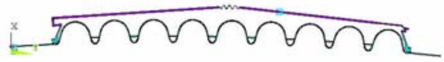
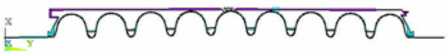
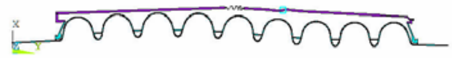


Figure 8: stresses in the bellow due to the dead loads and tuner weight

4.2 Eigenfrequency analysis

As seen in the design requirements it is important to check that the structure eigenfrequencies does not coincide with the frequency of RF repetition rate (1÷10 Hz). This is verified as shown in table 5.

Table 5: eigenfrequencies of assembly HT + cavity

n.	f [Hz]	Mode Shape
1	27.77	
2	51.66	
3	116.1	
4	305.9	

5 ADAPTATION TO LOW BETA ELLIPTICAL STRUCTURES

The simple geometry of the tuning device allows to adapt it to other cavities with minor modification. In particular, in the context of the HIPPI subproject of the CARE program [7], our group is going to equip the two low beta (0.47) 700 MHz elliptical cavities, developed for the TRASCO project, for high power pulsed measurements in CRYHOLAB at CEA/Saclay, to verify the feasibility of LFD compensation of these structures. The cavities have been tested in CW conditions up to 17 MV/m (61 MV/m peak electric and 100 mT peak magnetic fields) [8]. The test of these structures under pulsed operation is particularly significant for the feasibility studies of superconducting high power proton drivers.

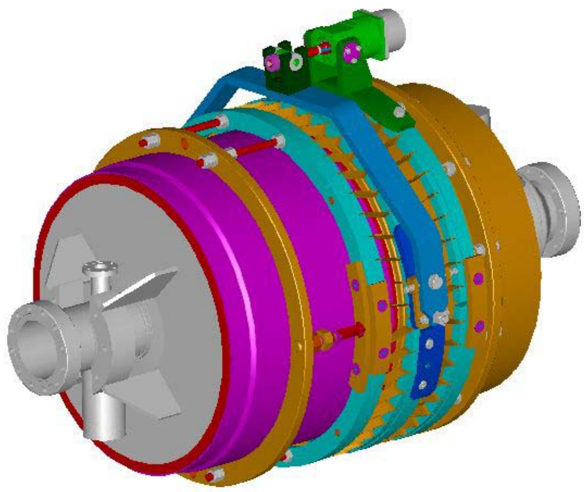


Figure 9: The preliminary layout of the scaled coaxial tuner for the 700 MHz 0.5 beta TRASCO cavity.

On the basis of the design procedures described in the preceding sections, a scaling of the coaxial tuner, and its adaptation to the TRASCO cavity case, has been performed, and the layout is shown in figure 9. The construction of the tuner prototypes for the HIPPI program is foreseen in late 2006, thus the final detailed engineering of the tuner will be finalized after the end of the tests that will be performed at DESY on the TESLA type tuner.

6 CONCLUSIONS

The functionalities of the coaxial tuner equipped with fast element have been described pointing out the requirements that drove its design.

Several analyses by means of simple spring models or by means of finite element method allowed us to verify the compatibility of the device with the specification of the TTF/Tesla cavities.

A major topic is represented by the performances of piezo actuators (or any other fast element used) at cryogenic temperature, but their behaviour is under study in many laboratories.

We plan to perform soon a test of a complete blade tuner prototype integrating an fast capability for LFD and microphonics compensation. We expect the tests will provide the final qualification of this solution, which is attractive in terms of compactness and longitudinal clearance needs.

7 REFERENCES

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