

# PERFORMANCE OF THE TUNER MECHANISM FOR SSR1 RESONATORS DURING FULLY INTEGRATED TESTS AT FERMILAB\*

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## Abstract

In the framework of the Proton Improvement Plan-II (PIP-II) at Fermilab, a cavity tuner was developed to control the frequency of 325 MHz spoke resonators (SSR1). The behavior of the tuner mechanism and compliance with technical specifications were investigated through a campaign of experimental tests in operating conditions in the spoke test cryostat (STC) and at room temperature. Figures of merit for the tuner such as tuning range, stiffness, components hysteresis and overall performance were measured and are reported in this paper.

## INTRODUCTION

With the goal of maintaining the cavity at the proper operational frequency: 325 MHz [1], the tuner was designed to compensate uncertainties in the frequency shift due to the cooldown from 293 K to 2 K and to minimize detuning caused by helium pressure fluctuations and microphonics perturbations. Cooldown uncertainties are estimated to be less than 135 kHz, while the amplitude of perturbations is estimated to be less than 1 kHz. These two values define respectively the requirements for coarse tuning and fine tuning. In order for the cavity to have a low pressure sensitivity ( $df/dp$ ), studies showed that the stiffness of the tuner as seen by the cavity (passive stiffness) must be greater than  $30 \text{ kN mm}^{-1}$ .

Figure 1 shows the tuner prototype that was developed.

The large scale tuning (135 kHz) is accomplished via a stepper motor actuating a threaded rod and traveling nut, translating rotational motion into axial motion of a double-lever mechanism, compressing and relaxing the cavity at one of the two beam-pipes. Fine tuning (1 kHz) is achieved with piezoelectric actuators (or piezos) which act as a fine tuning mechanism for the active compensation of perturbation sources like helium bath pressure fluctuations and mechanical vibrations. Other technical specifications for the tuner are described elsewhere [1, 2].

Figure 5 shows the operating principle of the double lever mechanism that allows coarse and fine tuning of the cavity. The two main arms hinged at one end and connected to the actuation system at the other end have a probe that tunes the cavity physically pushing on the beam pipe. The actuation system consists of a stepper motor held by a bracket and connected to a second arm. This arm is hinged at the other end and keeps the piezos in series with the motor.

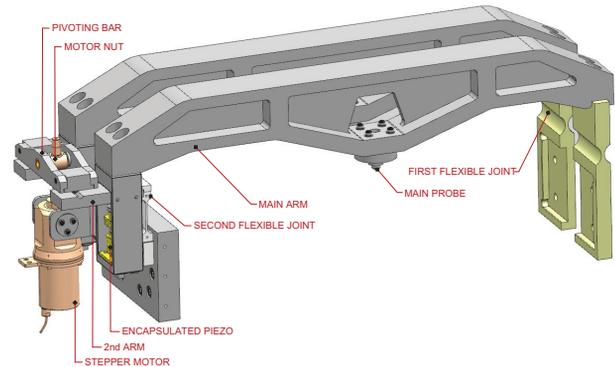


Figure 1: 3D model of the prototype model of SSR1 tuner.

## TESTS AT ROOM TEMPERATURE

Several checks and preliminary measurements were done at room temperature prior to installation onto a cavity for cold testing. All structural components were checked to ensure their compliance with fabrication drawings.

### Testing Encapsulated Piezos

The wire connections of the two encapsulated piezos were checked by measuring their resistance and impedance. Subsequently, both piezos were tested to monitor their elongation by applying different voltages from 0 V to 200 V (maximum applicable voltage), see Figure 2. The required stroke of  $68 \mu\text{m}$  at room temperature was achieved for both piezos. The piezos are controlled in voltage by 10 V stages during the scan and both present a hysteresis loop.

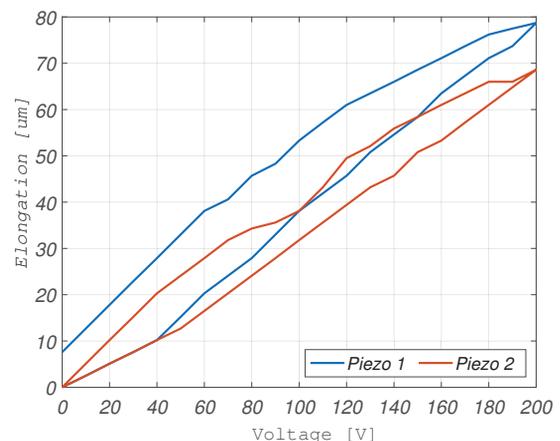


Figure 2: Elongation of Noliac piezos as a function of the voltage with an initial preload of 2000 N.

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### Tuner on the Test Bench

The tuner was entirely assembled on a tuner stand to check the kinematic and elastic behavior of the system, see Fig. 4. The main probes of the tuner are pushing against bars that have been machined to have the same stiffness of the cavity (about 21 kN/mm). Load cells and dial indicators were used to monitor the distribution of forces in the mechanism and displacements of targeted components.

**Tuning cycles - Loads** Several cycles were performed using the stepper motor and piezos. The entire system works as expected in the range of displacements needed to elastically tune the SSR1 cavity:  $x_{BPP} = 250 \mu\text{m}$ . The flexible joints worked in the elastic range and did not show any inelastic deformation. The stepper motor has reached several times its maximum load of 1300 N without noticeable issues. The exposure of the motor shaft to atmosphere was limited by purging the area with nitrogen. Both piezos were successfully actuated several times up to 200 V with different preloads.

The load measured in each of the two encapsulated piezos is the same in all working conditions. This was for the most part achieved by adopting a pivoting mechanism which automatically distributes the loads evenly between the two piezos. This will allow uniform pressure on the beam-pipe flange.

**Mechanical Advantages** Figure 3 shows the forces applied to the tuner components by the stepper motor ( $F_m$ ), both piezos ( $F_p$ ) and Nb-cavity ( $F_c$ ). The mechanical advantage at the motor and piezos is calculated in eq. 1 and eq. 2, respectively. The geometrical parameters for the prototype tuner were recently optimized and are slightly different from what was reported in [1].

$$T_m = \frac{L_1 + L_2}{L_2} \cdot \frac{S_1 + S_2}{S_2} = 7 \quad (1)$$

$$T_p = \frac{L_1 + L_2}{L_2} = 2.2 \quad (2)$$

Mechanical advantages of the lever-system at the motor and piezos was measured and they match the data above.

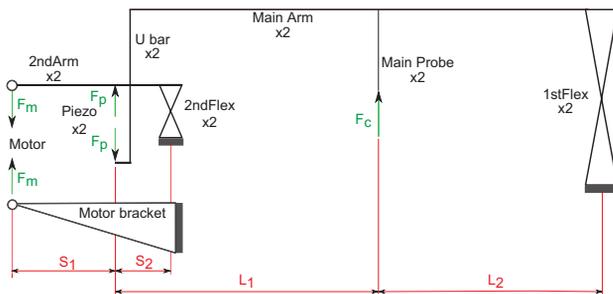


Figure 3: Scheme of force acting on the prototype tuner.  $L_1 = 353 \text{ mm}$ ,  $L_2 = 296 \text{ mm}$ ,  $S_1 = 67 \text{ mm}$ ,  $S_2 = 30 \text{ mm}$ .



Figure 4: Tuner mounted on a test stand for initial measurements at room temperature.

**Passive Stiffness** The passive stiffness of the system meets the specification of  $30 \text{ kN mm}^{-1}$ .

### Tuner on a Dressed SSR1 Cavity

The tuner was installed on a dressed SSR1 cavity (SIH-NR-107) and measurements were done to validate the efficiency of the mechanism both in coarse and fine regimes.

**Efficiencies** Using dial indicators, an efficiency of  $E_{ct} = 5.5\%$  was measured during the coarse tuning satisfying in fact the specification of  $E_{ct} = \frac{x_{BPPc}}{x_c} \leq 37\%$ . Translating the nut of the motor by a quantity  $x_c$  [unit of length], the displacement obtained at the beam-pipe port of the cavity ( $x_{BPP}$ ) is equal to  $0.05 \cdot x_c$ . Also, the specification in fine tuning mode was met,  $E_{ft} = \frac{x_{BPPf}}{x_f} \geq 17\%$ , having measured  $E_{ft} = 44\%$  with both piezos working and  $E_{ft} = 29\%$  with only one of the two piezos working. Finally it was verified that if one of the two piezos will fail in operation, the cavity can still be tuned with a fine tuning range bigger than the required range of 1 kHz.

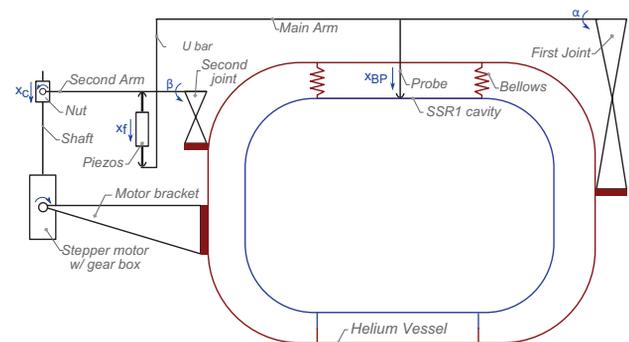


Figure 5: Schematic representation of the working principle of the SSR1 tuner.

## TESTS AT COLD TEMPERATURE

After completing all the checks and measurements at room temperature, cavity S1H-NR-107 with the tuner was assembled in STC with high-power coupler, see Figure 6.

By adjusting the two screws for the fine alignment of the tuner, the probes were set with a 1.40 mm gap from the beam-pipe flange of the cavity such that at the end of the cooldown, due to the effect of the differential shrinkage between niobium and stainless steel, there would be a gap of 0.40 mm. This estimate was done based on results of thermal/structural FE analysis. Maintaining a gap between the tuner mechanism and the cavity beam pipe allows to record the frequency shift for the cavity due solely to the cool down effects. Additionally, such gap is set to avoid any damage to the mechanism.

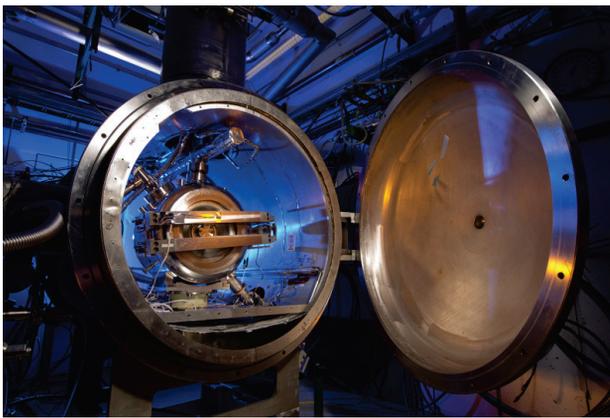


Figure 6: Installation of SSR1 cavity (S1H-NR-107) with tuner and coupler into the Spoke cavity Test Cryostat (STC) at Fermilab.

### Cooldown

It was of interest to investigate the behavior of the cavity frequency and temperatures of components during the cooldown from 293 K to 2 K.

**Temperatures** Several resistance temperature detectors (RTDs) were installed on the tuner components: housing of piezo 1, housing of piezo 2, motor housing, first flexible joint, and main arm, to check the distribution of temperature in operating conditions. Also, the stepper motor has a thermocouple in housing. Figure 7 shows the data collected by the temperature sensors as function of time during the cooldown of the SSR1 cavity. The motor housing was also connected to 80 K lines by thermal straps. The results will be useful as inputs in thermal/structural finite-element analysis for studying and optimizing the behavior of the system (cavity and tuner) due to thermal contraction of the materials during cooldown.

**Frequency Shift** At the end of the cooldown process, when the niobium cavity reached 2 K, the tuner probes were

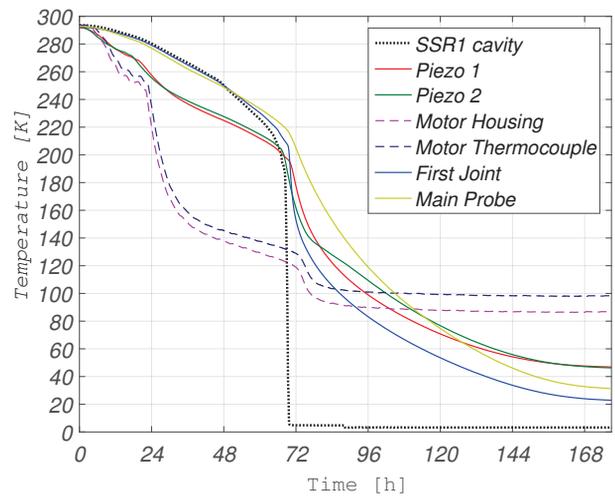


Figure 7: Temperature profiles of targeted components during cooldown process of the SSR1 cavity (S1H-NR-107).

not touching the beam-pipe flanges, as expected. The resonant frequency of the cavity shifted +337.721 kHz, from 324.974 009 MHz to 325.311 730 MHz. The estimated frequency shift by finite-element analysis was +285 kHz. This result will be used as a reference number to properly tune (inelastic tuning) the next dressed cavities so that the resonant frequency of the cavity will be as close as possible to the targeted frequency of 325.000 MHz at 2 K with the tuner engaged.

### Coarse Tuning Mode

**Coarse Tuning Range** The “0-position” of the tuner, see Fig. 8, when the probes are just in contact with the beam-pipe flange observing a frequency shifts of few tens of Hertz, was found moving the stepper motor of about 27000 steps toward the cavity at the resonant frequency of 325.311 700 MHz. It has to be noted that 27000 steps corresponds to a probes displacement of about 0.4 mm, the gap that was expected setting the probes at a distance of 1.40 mm during the setup.

Using the stepper motor, the tuner was put in the “start-position”, which consists in shifting the resonant frequency of the cavity of -80 kHz, see Fig. 8. In this configuration both piezos are preloaded with 840 N, as required in the vendor datasheet. Then, the full tuning range of 135 kHz, from the “start-point” to the “end-position”, was scanned by 25 kHz stages checking the linear-elastic behavior of the cavity and tuner after each stage. Fitting of the range scan gives a motor resolution of -4.85 Hz/step. The full cavity range is 26000 steps for 135 kHz.

**Motor - Load** The force seen by the motor goes from 0 N when the motor is in “0-position” to 1230 N with the tuner in “end-position”. Those forces are estimated using the frequency shift from Fig. 8, the mechanical advantage of Eq. 1, the cavity sensitivity  $df/dL=520$  kHz/mm, and cavity

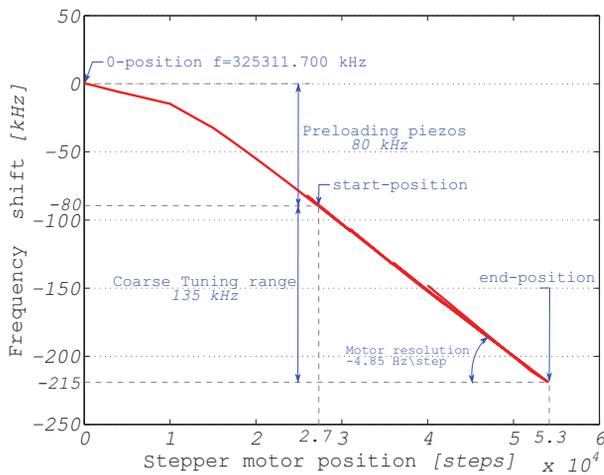


Figure 8: Tuner setup in the tuning range.

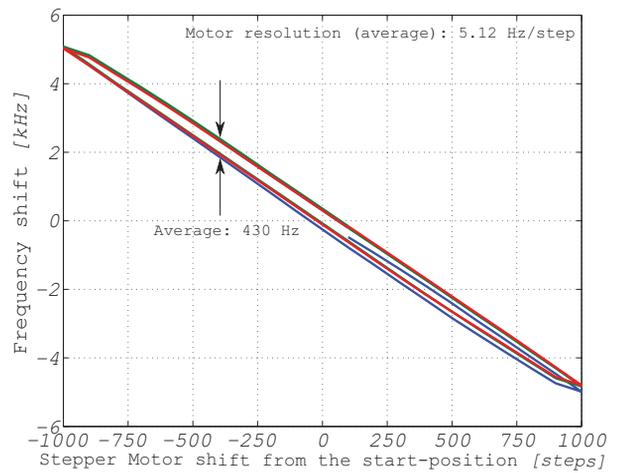


Figure 9: Scan around the “start-position” moving the stepper motor  $\pm 1000$  steps by 100 step stages.

stiffness  $k_c = 21000$  N/mm. The maximum force is below the acceptable force for the motor.

**Motor - Temperature** It was interesting to monitor temperatures at various locations on the tuner during this activity. Running the motor for this test over about an hour significantly raised the temperature of the in-motor thermocouple from 100 K to 330 K, as well as the housing from 85 K to 150 K. It is clear that the duty cycle of the motor should be lowered in future measurements to keep the motor temperature lower. It is estimated that the motor was run approximately  $10^5$  step/hour during this time. Future measurements will endeavor to keep the step rate to half this or lower, with temperatures being monitored to see if a further reduction is required, though in operating condition the stepper motor will be used for an amount of time that does not exceed 20 minutes.

**Motor Scans** The stepper motor scans were done around the “start-position” (see Fig. 9) and the “end-position” (see Fig. 10) of the tuning range by 100 step stages. Frequency per step was measured at the end outside of the lash region, and the frequency spread from hysteresis was measured in the same region. Hysteresis went up from 430 Hz to 1.535 kHz. The averaged motor resolution went down from 5.12 Hz/step to 4.69 Hz/step.

*Fine Tuning Mode*

The tuning range in fine tuning mode was measured positioning the tuner in the “start-position” and “end-position” while a DC bias was applied to each piezos individually. The piezomaster box was used with a drive voltage applied by hand. The piezomaster gain as well as the monitor port gain was calibrated beforehand, and the applied voltage was swept from 0 V to 100 V and back by 25 V steps. It was decided to follow a conservative approach on the use of the piezos, limiting the maximum voltage to 100 V instead of going up to the limit of 200 V. Because the cable for applying the same voltage to both piezos was broken, voltage

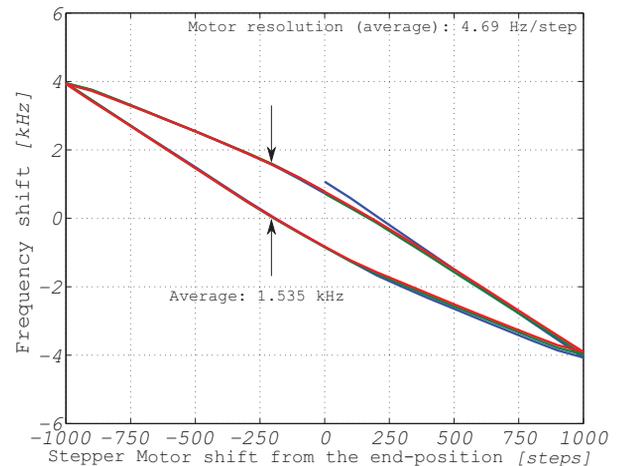


Figure 10: Scan around the “end-position” moving the stepper motor  $\pm 1000$  steps by 100 step stages.

could only be applied to one piezos at a time, which means that about half of the stroke is lost due to the mechanical disadvantage of the mechanism in this working condition.

**Fine Tuning Range - Start Position** Figure 11 shows the measurement of both piezos with the tuner positioned at the “start-position” (low preloading) of the tuning range. A full range of about 650 Hz per 100 V applied was measured. In normal operating conditions, with both piezos working simultaneously up to 200 V, the fine tuning range would be of about 2.5 kHz exceeding the requirements on range 1 kHz. The tuner hysteresis was about 120 Hz for both piezos applying 100 V.

**Fine Tuning range - End Position** Figure 12 shows the measurement of both piezos with the tuner positioned at the “end-position” (high preloading) of the tuning range. A full range of about 300 Hz was measured. In normal operating conditions, both piezos working simultaneously up to 200 V,

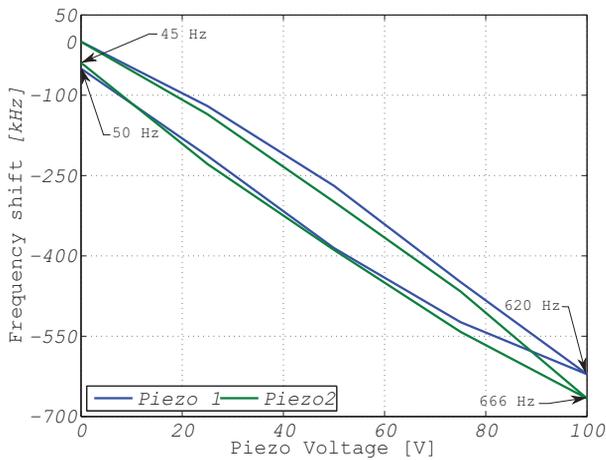


Figure 11: Scan around the “start-position” (lowest preload) actuating one piezo at the time by 25 V stages up to 100 V.

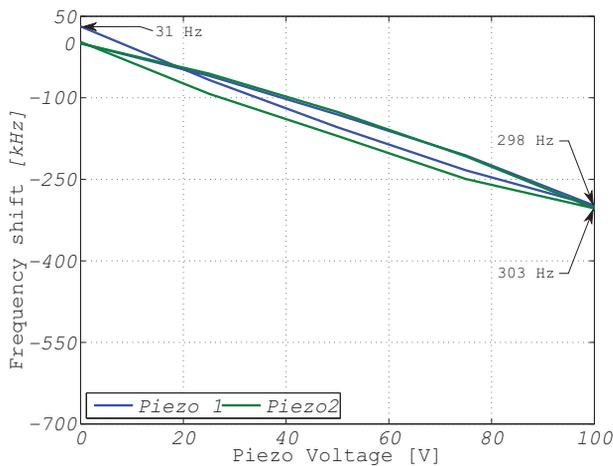


Figure 12: Scan around the “start-position” (lowest preload) actuating one piezo at the time by 25 V stages up to 100 V.

the fine tuning range would be of about 1.2 kHz. Also in worst working condition, the specification of the fine tuning range is satisfied. The tuner hysteresis was about 100 Hz for both piezos applying 100 V.

## CONCLUSION AND FUTURE WORK

The validation of the design for this first prototype of tuner mechanism for the SSR1 cavity is complete. All specifications in terms of stiffness, tuning ranges, tuning efficiencies, and resolutions of the active components are met. Also, this prototype tuner was successfully used in preliminary studies of resonant control [3] for SSR1 cavities. The fast tuner was used to drive cavity characterization routines, including mechanical to electrical transfer functions.

Next activities will be aimed at defining an acceptable threshold of hysteresis for both motor and piezos, that does not influence the dynamic behavior of the tuner. Additionally, studies of active resonance stabilization were done, but

a through study of interaction between tuner loading and performance was not completed.

## REFERENCES

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