SSR1 TUNER MECHANISM: PASSIVE AND ACTIVE DEVICE*

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Abstract

In this paper we present the methodology adopted in designing the mechanism responsible for controlling the resonant frequency of Single Spoke Resonators of first type (SSR1). Such device is capable of compensating the effects of external perturbations, such as pressure fluctuations and microphonics, on the frequency of SSR1. The compensation is achieved through active responses via an actuation system and passive responses which are inherent to the elastic behavior of the overall system. The first experiences in the design, assembly, QA and testing are reported.

INTRODUCTION

The SSR1 cryomodule for the project PXIE [1] contains superconducting cavities with very narrow bandwidth in operating condition at 2 K. Due to that, a particular effort is needed to keep the resonant frequency of the cavity at its nominal value of 325 MHz. Even tough the cavity receives an inelastic tuning before the cooldown from room temperature to 2 K, there is a range of uncertainty of the final frequency that has to be adjusted by the tuner (coarse tuning). On top of that, there are other external noises generally known as microphonic that disturb the resonant frequency of the cavity in operation. The tuner is also used to minimize and possibly cancel that effect (fine tuning).

The tuning device for the SSR1 cavities of generation 3 (SSR1-G3) [2] has to operate only on one of the beam-pipe regions of the cavity and only generates forces directed towards the cavity (push only). The resonant frequency of the cavity is modified by adjusting the spacing between the cavity end-wall and the spoke. Controlling this gap allows to maintain the frequency near the nominal value of 325 MHz.

An expansion joint (bellows) structurally connects the Nb-cavity to the He-vessel to facilitate the tuning. The axial stiffness of the bellows is negligible compared to the stiffness of the Nb-cavity of $k_{cav} = 30\,\mathrm{N\,\mu m^{-1}}$. The geometry and structure of the He-vessel is such that it accommodates the tuner's supports on the cylindrical shell, where the reacting forces during the tuning do not affect the high sensitive zones of the SRF cavity.

SPECIFICATIONS

The architecture and efficiency of the tuner must be such that the range of the RF frequency change has to be at least of 135 kHz and 1 kHz, while operating in coarse and fine tuning mode, respectively. The cavity has a sensitivity at the beam-pipe of $\frac{df}{dL} = 540\,\mathrm{kHz\,mm^{-1}}$. Thus, the displacement at the beam pipe has to be of $x_{BPc} \geq 250\,\mu\mathrm{m}$ in coarse tuning mode and $x_{BPf} \geq 1.85\,\mu\mathrm{m}$ in fine tuning mode. Moreover the tuner's stiffness seen by the cavity (passive stiffness) must be greater than $30\,\mathrm{kN\,mm^{-1}}$ in order to have a system with a pressure sensitivity $\frac{df}{dp} \leq 25$ Hz/Torr.

The reliability of a frequency-tuning system is always of great concern. The actuators are prone to failures if not integrated and operated carefully. Failure of the tuning system has an immediate impact on the accelerator complex. Due to the concerns on reliability, the system shall be designed to allow the replacement of the actuating devices in case of failure or deterioration. Maintenance operations shall be simplified where possible considering the system will be serviced manually through access ports in the vacuum vessel of the cryomodule.

CONCEPTUAL DESIGN

Based on the performance of the first SSR1 tuner [3] and other R&D activities, it was decided to develop a lever mechanism actuated by a Phytron stepper motor assembly and Noliac piezos (Table 1) to meet the PXIE specifications.

Table 1: Performance of Phytron Stepper Motor Assembly and Noliac Piezo-electric Actuators to be Used

Parameter	Value
Stepper motor with gear box	
Max force	1300 N
Resolution	0.1 µm
Piezo	
Stroke (x_f) at 293 K	68 µm
Stroke (x_f) at 20 K	15 µm
Max operating force	2700 N
Min operating force	840 N

Figure 1 shows the scheme of the double lever mechanism that allows the coarse and fine tuning of the cavity. A main arm hinged at one end and connected to the actuation system at the other end has 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 2 shows the scheme of forces applied to the tuner components by the stepper motor (F_m), piezos (F_p) and Nb-cavity (F_c). Assuming that the losses in the system (i.e. friction) are negligible compared to the force for tuning the cavity, a good estimation of the range of force applied at the tuner's probe, F_c, during the tuning is calculated in eq. 1. The mechanical advantage at the motor and piezos is

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calculated in eq. 2 and eq. 3, respectively. The force at the motor F_m and piezo F_p are calculated in 4 and 5.

$$0 \leq F_c \leq k_{cav}\left(x_{BPc} + x_{BPf}\right) \simeq 7500\,\mathrm{N} \quad (1)$$

$$T_m = \frac{L_1 + L_2}{L_2} \cdot \frac{S_1 + S_2}{S_2} = 6.5 \quad (2)$$

$$T_p = \frac{L_1 + L_2}{L_2} = 2 \quad (3)$$

$$0 \leq F_m \leq \frac{F_c}{T_m} = 1150\,\mathrm{N} \quad (4)$$

$$0 \leq F_p \leq \frac{F_c}{T_p} = 3750\,\mathrm{N} \quad (5)$$

OPERATING MODE

Coarse Tuning

With reference to Figure 1, when the motor is actuated it causes a translation (x_c) at the nut and consequently the rotation (β) of the second arm. The two piezo-electric actuators transmit forces from the second arms to the main arms by means of pivoting connections which protect the ceramic elements from shear forces. The main arms rotate by an angle α and the two probes push on the cavity displacing the beam-pipe by x_{BPc}.

The mechanical advantages of the double lever mechanism at the motor permits to reduce the maximum force needed for the coarse tuning from the 7500 N at the beam pipe to the 1150 N at the motor. This value of force is lower than the maximum force that the motor can deliver (see 1).

It is requested that at each step of the motor corresponds a frequency shift of the cavity of ≤ 20 Hz, that means $x_{BPc} \leq$ 37 nm. Knowing that a single step of the motor corresponds $x_c = 100$ nm, the system has to satisfy the condition $\frac{x_{BPc}}{x_c} \leq$ 37%. Thanks to the geometry of the system, this condition is already satisfied, even if the mechanism would be infinitely rigid: $\frac{x_{BPc}}{x_c} = \frac{1}{T_m} = 15.4\%$.

Fine Tuning

After that the piezos have been properly preloaded, they can be used for the fine tuning. Keeping the motor locked and electrically powering the piezos, they increase the length of x_f causing a rotation α of the main arm and a displacement of the beam pipe of x_{BPf}. Since the stroke of the piezos at the operating temperature (~ 20 K) is limited to $0 \leq x_f \leq$ 15 µm and the specified tuning range has to be $\geq$ 1 kHz ($\Rightarrow x_{BP} \geq 1.85$ µm), the system will be designed such that taking into account the mechanical disadvantage and the flexibility of the system, the following condition of efficiency (E_{ft}) must be satisfied:

$$E_{ft} = \frac{x_{BPf}}{x_f} \geq 17\% \quad (6)$$

Passive Tuning

This is a condition that is not often taken into account during the design of a tuner. The pressure sensitivity of the dressed SSR1 cavity is also function of the tuner's stiffness seen by the cavity. When there is a pressure fluctuation in the He-bath, the entire cavity is subject to deformations and the beam pipe moves toward the probe of the tuner. It has been studied that a value of "passive stiffness" greater than 30 N µm^{-1} helps to minimize the $\frac{df}{dp}$ of the cavity to few units, possibly to zero.

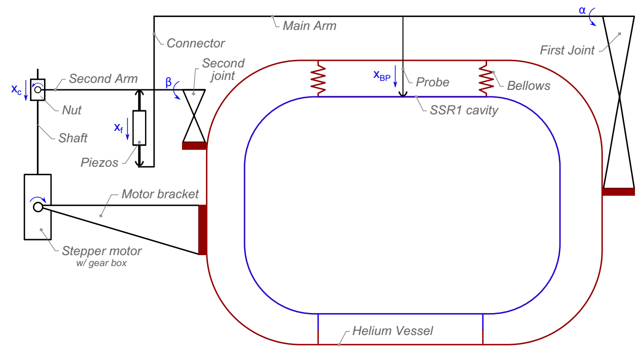

Figure 1: Schematic for the tuning system showing the cavity inside the helium vessel.

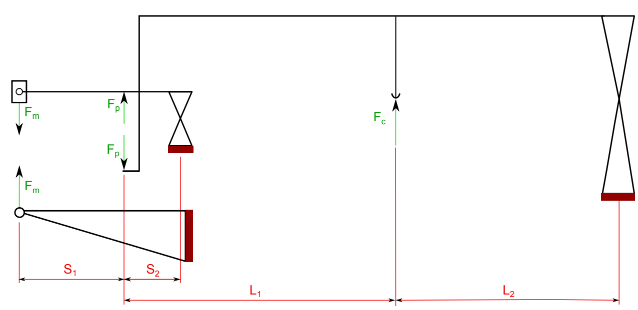

Figure 2: Scheme of force acting on the Tuner. L_1 = 350 mm, L_2 = 350 mm, S_1 = 67 mm, S_2 = 30 mm

DESIGN

Once the kinematics and the preliminary specification were checked, the design of solid parts started getting the device shown in Figure 3 as a result.

The main structural components are made of Stainless Steel 316L because of its low magnetic permeability and also to have the same coefficient of thermal contraction of the He-vessel during the cooldown.

An encapsulation for the ceramic piezos was specifically designed to make sure they work always aligned with the load and to reduce as much as possible the components of shear forces, see Figure 4. Due to this, the entire encapsulation is held by two spherical contacts and a bellows that assure the centering. It has been called "floating piezo" since it can adjust its position pivoting around the two spherical contacts by deforming the bellows. Flexible joints were used

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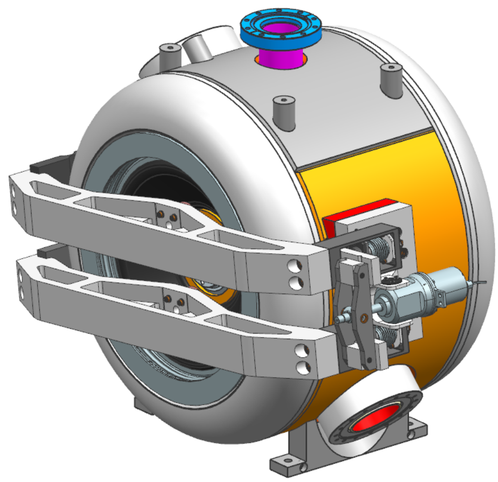

Figure 3: 3D model of the Tuner assembled on the SSR1-G3 cavity.

Figure 4: Assemblies of encapsulated ceramic piezos.

as hinges to reduce the backlash phenomena and to improve alignment of the parts. The type, shape and material of the these joints were defined with the support of FE analyses and experimental tests.

All spherical contacts were designed using ceramic balls on stainless steel in order to minimize the friction coefficient. The contacts were studied and optimized following the Hertzian theory of non-adhesive elastic contact.

The alignment of the components is a challenge. Adjusting screws have been integrated in the design to compensate the variances due to the manufacturing processes.

The entire actuation group is assembled on a removable cartridge in order to increase its reliability allowing the removal from the cryomodule in the case of failure of one of the actuating components. Figure 5 shows the ports of the Cryomodule that give the access to the actuation group and from where it would be removed for maintenance.

In order to satisfy the conditions of efficiency (eq. 6) and "passive stiffness", lumped parameter models of all operating mode were developed in order to avoid weak links in the mechanism and to have the proper contribution from each component, contact and joint in terms of stiffness. Of course, calculations and FE analyses were done to check the deformations (stiffness) and the stresses of each component to achieve the specifications.

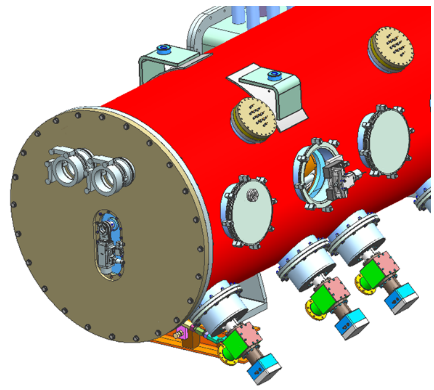

Figure 5: Access ports to the removable cartridge.

FIRST TESTS AND FUTURE WORKS

The first prototype of the tuner that was checked and assembled on a frame reproducing the tuner's supports of the cavity is shown in Figure 6.

Preliminary tests at room temperature were performed in order to check the alignment of the parts, the symmetry of the loads in the two piezos and the deformation at the probes. Of course, more tests will be necessary to fully characterize its behavior and the respect of the specifications.

The two encapsulated piezo assemblies were tested at room and cryogenic temperature. The strokes under different loading conditions were measured and it meets the performance declared by the vendor.

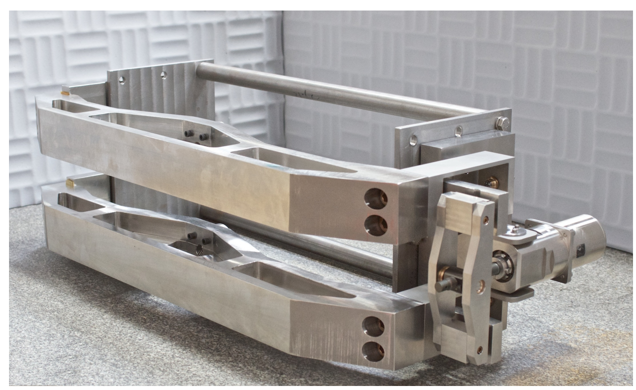

Figure 6: First prototype of the SSR1 double lever tuner.

ACKNOWLEDGMENT

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REFERENCES

[1] T. Nicol et al., "SSR1 Cryomodule Design for PXIE", PAC2013, Pasadena, California, THPMA09.

[2] L. Ristori et al., "Design of SSR1 Spoke Resonators for PXIE", IPAC2012, New Orleans, Louisiana, WEPPC057.

[3] Y. Pischalnikov et al., "A Tuner for a 325 MHz SRF Spoke Cavity" SRF2009, Berlin, Germany, THPPO043.

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