ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV013

VALIDATION OF THE 650 MHz SRF CAVITY TUNER FOR PIP-II AT 2 K*

C. Contreras-Martinez[†,1], S. Chandrasekaran, S. Cheban, G. Eremeev, F. Furuta, T. Khabiboulline, Y. Pischalnikov, O. Prokofiev, A. Sukhanov, JC. Yun, Fermilab, Batavia, IL, USA
[1]also at Michigan State University, East Lansing, MI, USA

Abstract

The PIP-II linac will include thirty-six β_G=0.61 and twenty-four β_G=0.92 650 MHz 5-cell elliptical SRF cavities. Each cavity will be equipped with a tuning system consisting of a double lever slow tuner for coarse frequency tuning and a piezoelectric actuator for fine frequency tuning. One cavity equipped with an SRF tuner has been tested in the horizontal test stand at Fermilab. Results of testing the cavity-tuner system will be presented.

INTRODUCTION

The proton improvement plan (PIP)-II linac section being built at Fermilab will consist of five classes of superconducting RF (SRF) cavities made of niobium. Two types of elliptical cavities, the low beta (LB) cavity at β_G= 0.61 and the high beta (HB) cavity at β_G= 0.92, are used to accelerate the proton beam from 185 MeV to 800 MeV. The beam then will be injected into the booster synchrotron at 800 MeV and will exit with a beam energy of 8 GeV. Lastly, the proton beam goes into the main injector ring resulting in a proton beam energy of 120 GeV and power of 1.2 MW. The proton beam will hit a target producing a secondary kaon beam which decays into neutrinos. The proton beam will also be used for experiments in the g-2 and mu2e collaborations at Fermilab. The neutrino beams travel 800 miles through the earth from Fermilab to an underground detector in Sanford, South Dakota [1].

The prototype HB 650 cryomodule (CM) will have a mix of the β_G= 0.92 and legacy β_G =0.90 cavities. The legacy cavity was jacketed first and was tested in the horizontal configuration The double lever arm tuner was tested at room temperature on a $\beta_G = 0.9$ five cell 650 MHz elliptical cavity [2]. In this paper the testing of the double lever arm tuner on the cavity at 2 K is presented. The cavity was placed in the recently upgraded cryostat [3] at the Meson Detector Building (MDB) at Fermilab, pictured in Fig. 1. This double lever tuner will be used for both the HB and LB 650 MHz elliptical cavities. The tuner specifications for the HB and LB 650 MHz cavities are shown in Table 1. The SRF cavity tuner has three roles. It is needed for active microphonics compensation. It is also used for moving the cavities to the nominal frequency after cooling to 2 K. Lastly, it is used for protecting the cavity during pressure tests. There are two components to the tuner, one is the slow and coarse frequency tuning component consisting of a stepper motor. The other is the fast and fine frequency tuning component composed of piezoelectric actuators.

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. Additional support provided by award number DE-SC0018362 and Michigan State University.
† ccontrer@fnal.gov

The slow and coarse electromechanical component of the double lever arm tuner consists of a stepper motor manufactured by Phytron. The stepper motor has been tested in ultra-high vacuum and at cryogenic temperature in the cryomodule environment. Accelerated lifetime tests done at Fermilab demonstrate that this stepper motor will survive prolonged operation for the typical linac lifetime of 25 years [4, 5]. The cavity in the cryomodule with beam and high power is expected to produce field emissions and other radiation which can be detrimental to the stepper motor. No performance degradation was observed after an irradiation hardness test (gamma rays) with a dose level of 5×10^8 Rad, demonstrating that the stepper motor can survive under these operating conditions [5].

The fast and fine tuner component consists of two piezoelectric actuator capsules. The piezoelectric actuators are used for fast and fine frequency tuning control of microphonics. The piezoelectric actuators are designed and fabricated by Physik Instrumente (PI) per Fermilab specifications. The design consists of two 10×10×18 mm PICMA lead zirconate titanate (PZT) ceramics glued together and encapsulated in a stainless-steel cylindrical shell.

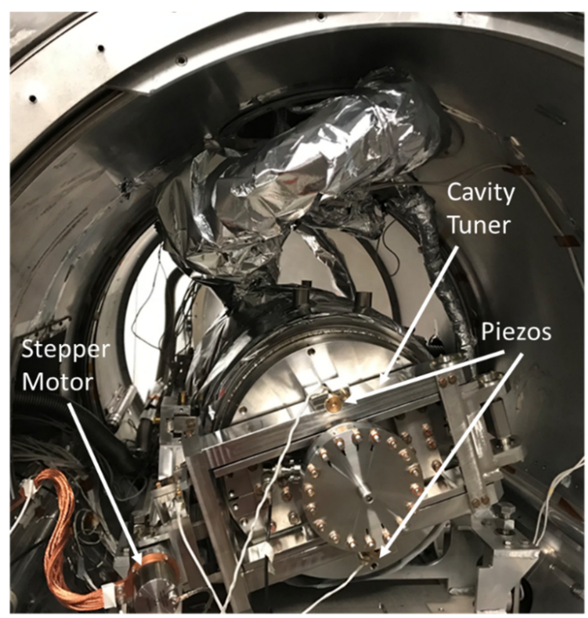

Figure 1: 650 MHz $\beta_G = 0.90$ with tuner and other ancillaries inside the STC cryostat at the MDB facility in Fermilab.

The accelerated lifetime test demonstrates that the piezo can sustain 2×10^{10} pulses with a peak-to-peak amplitude of 2 V, which is equivalent to 25 years of operation of the LCLS-II linac. The same number of cycles are expected for the PIP-II linac. The irradiation test, with same parameters as the stepper motor test, also showed minimal degradation

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Table 1 : 650 MHz Cavity and Tuner Specifications for Different Geometries

	$\beta_G = 0.9$	$\beta_G = 0.92$	$\beta_G = 0.61$
Cavity Stiffness [kN/mm]	20	5	4
Cavity Tuning Sensitivity [Hz/µm]	180	150	240
Tuner System Stiffness [kN/m]	≥ 40	≥ 40	≥ 40
Lowest Mechanical Resonance of Cavity-tuner System [Hz]	>100	>100	>100
Slow Tuner Frequency Range [kHz]	100	200	200
Stepper Motor Resolution [Hz/step]	≤ 1	≤1	≤1
Slow Tuner Hysteresis [Hz]	≤ 100	≤ 100	≤ 100
Piezo Tuner Frequency Range (at 120 V) [kHz]	1.2	1.2	1.2
Piezo Tuner Resolution [Hz]	<0.5	<0.5	<0.5

for this actuator [5]. For active microphonics compensation, the tuner maintains the frequency of the cavity at the accelerator operating frequency. This will ensure that the gradient of the cavity is kept at the nominal value, and similarly for the phase. Minimizing the detuning of the cavity with a fast tuner will reduce the overall RF power needed to compensate for the detuning.

SLOW AND COARSE TUNING COMPONENT

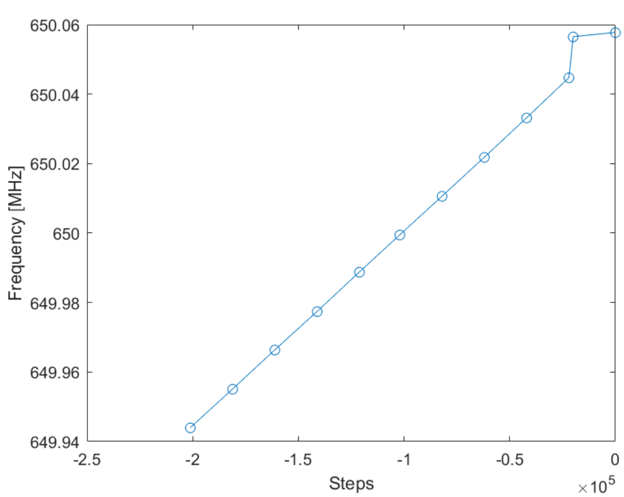

Figure 2: Tuner operation after cooldown to 2 K and further compression to demonstrate the range of the tuner.

The stepper motor consists of a threaded rod that drives a nut attached to the motor arm which then compresses the cavity. The tuner can only compress the cavity to lower the frequency. To complete one whole turn on the spindle the motor moves 10^4 steps. One whole turn on the spindle is equal to a 1 mm linear translation of the motor arm. Based on the kinematics of this tuner, the ratio of displacement on the motor shaft to the one on the cavity is 18. The stepper motor can deliver up to 1.3 kN of force at 2 K [5]. The tuner was tested on the 650 MHz $\beta_G = 0.9$ dressed cavity shown in Fig. 1. Once the cavity is cooled to 2 K the frequency will not be exactly at 650MHz.

The value of the frequency is set up during the field-flatness inelastic tuning so that it is slightly higher than the 650 MHz value for the tuner to be engaged with the cavity. This procedure is taken since the tuner can only compress the cavity, lowering the cavity frequency. The frequency of the cavity at 2 K before tuning was 650.06 MHz and is known as the 2 K cold-landing frequency $F_{2K\_Landing}$ where the tuner is unrestrained. A total of 10^8 steps were required to compress the cavity to 650 MHz which is shown in Fig. 2. An additional 10^8 steps were implemented to measure the range of the tuner and verify that no limit switches would be tripped during the movement. The total range measured from this compression was 120 kHz, this is higher than the specification given in Table 1 for the $\beta_G = 0.9$ value of 100 kHz. This range allows the cavity to have a greater initial frequency of up to 100 kHz above the nominal 650 MHz value.

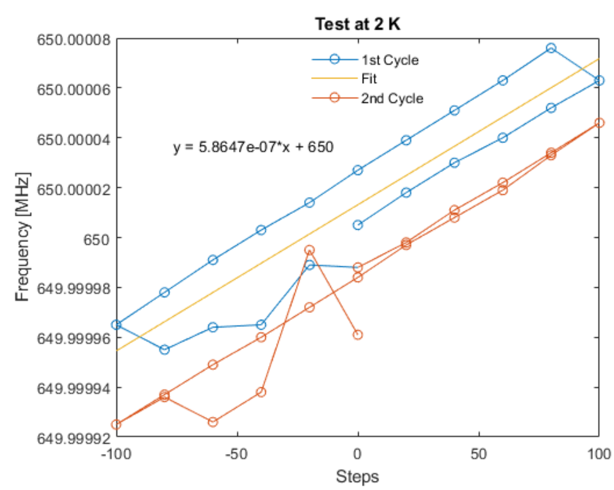

Figure 3: Short step hysteresis of the stepper motor.

The hysteresis of the stepper motor was tested by first operating it in short step increments and then in large step increments. In the short-range hysteresis with increments of 200 steps, the difference between the compression and relaxation sweep is 30 Hz, as shown in Fig. 3. The 30 Hz value of the slow tuner hysteresis is consistent with the stepper motor actuator backlash measured with the LCLS-II tuner [6]. This is also within the hysteresis specification given in Table 1. The sensitivity of the tuner in this range is 0.58 Hz/step also within the specification given in Table 1. In the long-range hysteresis with a span of 10^8 steps,

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shown in Fig. 4, the sensitivity is 0.57 Hz/step. These values demonstrate that the stepper motor can tune the cavity to 650 MHz and has a large range. The same tuner will be used for the 650 MHz $\beta_G = 0.61$ and $\beta_G = 0.92$ cavities which have a lower cavity stiffness of 4 kN/mm compared to the 20 kN/mm stiffness of the $\beta_G = 0.9$ cavity [2]. It is therefore expected that the tuner sensitivity will be greater for these cavities due to their smaller stiffness (see Table 1).

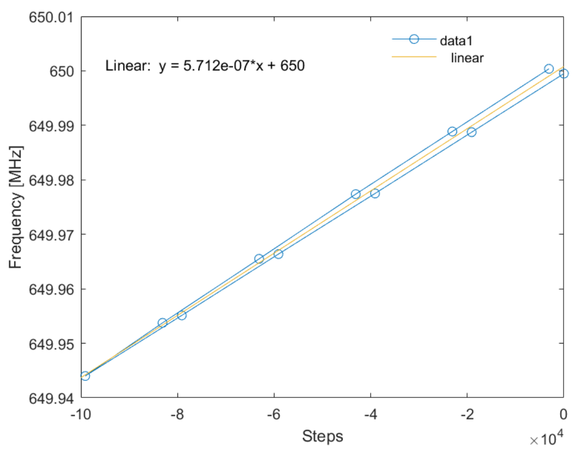

Figure 4: Large step stepper motor hysteresis.

FAST AND FINE TUNING COMPONENT

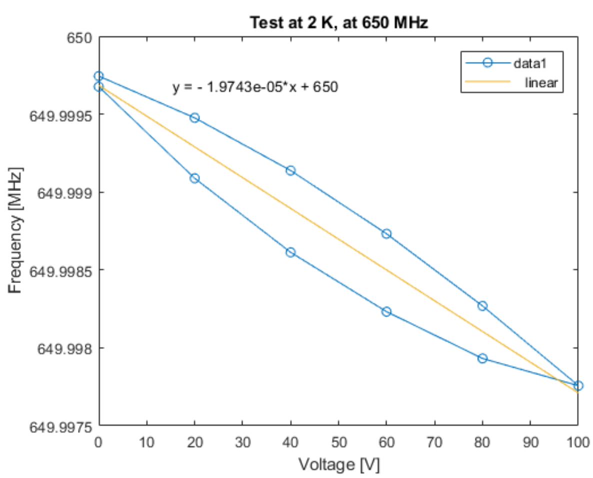

Figure 5: Piezo hysteresis of both capsules with 20 V intervals.

The tuner will consist of two piezo capsules which contact the cavity. The piezo actuator can expand by 34±2 µm when 100 V is applied at room temperature. The piezo displacement was studied on the 650 MHz cavity at 2 K, with results shown in Fig. 5. At 100 V on both piezo capsules, the cavity frequency shift was -1.97 kHz, which is higher than the specification given in Table 1. This gives a frequency sensitivity of 19.7 Hz/V. The piezo can be modulated by small increments such as 25 mV being able achieve a piezo resolution of 0.5 Hz which is within specification given in Table 1. Note that smaller voltage increments can be used. The frequency sensitivity measured at room temperature was 36 Hz/V [2]. The temperature of the piezo can be estimated to be in the range of 95 to 105 K, based on the results of the piezo stroke displacement characterization at cryogenic temperatures [7]. If only a single piezo capsule was used at 100 V, the frequency shift would only be 985 Hz. The expected detuning from microphonics of the cavity operated in CW mode is on the order of 5-50 Hz. The piezo actuators therefore provide sufficient range for compensation [8].

The $\beta_G = 0.9$ cavity has a stiffness of 20 kN/mm. It is expected that the load on the piezos will be 7 kN, which is roughly double the blocking forces at 3.8 kN. If a larger force is applied to the piezos there is a high probability that it could become depolarized. A room temperature test was therefore performed on the piezo displacement before and after a 7 kN force was applied to check for depolarization. A 7 kN force is applied to the piezo and then released. Results shown in Fig. 6 demonstrate that this does not affect the piezo stroke displacement. A more rigorous study of the piezo actuator under load is presented in Ref. [9]. The results show that the piezo can operate in high-stress environments with a force equal to or below 7 kN.

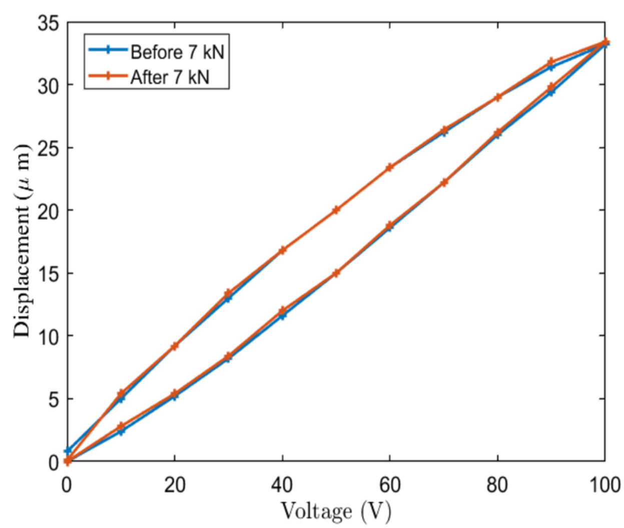

Figure 6: Piezo hysteresis before and after a 7 kN force was applied at room temperature.

CONCLUSION

The double lever tuner for the 650 MHz elliptical was tested for the first time at 2 K inside a cryostat. The results show that the slow-coarse range for the $\beta_G = 0.9$ cavity is 120 kHz. The hysteresis for the slow tuner is 30 Hz, consistent with the results in [6] and within specifications shown in Table 1. The fast-fine component test yielded a response of 19.7 Hz/V. This gives a large range for compensation of microphonics for CW operation and complements slow tuner compensation with fine frequency adjustment. Since the cavity has a large stiffness, the forces on the piezos will be large. A large force applied to the piezo can lead to depolarization. Results after application of 7 kN longitudinal force demonstrated that the piezo stoke displacement is not affected. Thus, the double lever tuner is capable of operation in the PIP-II linac by exceeding the specification of the PIP-II project.

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ACKNOWLEDGEMENTS

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with U.S. Department of Energy, Office of Science, Office of High Energy Physics.

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