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FREQUENCY TUNER DEVELOPMENT AT CORNELL FOR THE RAON HALF-WAVE-RESONATORS*

M. Ge†, F. Furuta, T. Gruber, S. Hartman, M. Liepe, J. Maniscalco, T. O'Connell, P. Pamel, J. Sears, V. Veshcherevich, Cornell University, Ithaca, New York, USA;
B.H. Choi, J. Joo, J.W. Kim, W.K. Kim, J. Lee, I. Shin, Institute for Basic Science, Daejeon, Korea.

Abstract

The superconducting 162.5MHz half-wave-resonators for the RAON project require a slow frequency tuner that can provide at least 80 kHz tuning range. Cornell University has designed, prototyped, and tested a tuner for these half-wave-resonators. In this paper, we present the tuner design, prototype fabrication, test insert preparation, long-term testing and tuner performance test results at cryogenic temperature. The performance of the tuner is analyzed in detail.

INTRODUCTION

Two half-wave-resonator (HWR) cavities will be housed in each HWR cryomodule for the ROAN accelerator [1-3]. Each HWR requires an individual slow frequency tuner that can shift the cavity RF frequency by at least 80 kHz. Cornell University developed a prototype HWR tuner, which is based on the pneumatic tuner developed by Argonne National Laboratory (ANL) [4]. The ANL pneumatic tuner requires a pressure regulation system to control tuning amounts; as an alternative way, we adopted a scissor section mounted with a cryogenic stepper-motor to replace the bellow section of the pneumatic tuner. In this way, the HWR tuner will be merely driven by electrical signals.

For the tuner prototyping, we performed long-term tests at room temperature and cold tests in a liquid nitrogen bath (temperature 77K) to optimize the tuner mechanical structure prior to the final cryogenic (4.2K-2K) testing of the tuner on a HWR prototype. During the tuner cryogenic tests, the frequency hysteresis curves were measured at temperatures of 4.2K and 2K, demonstrating that the tuner can shift the HWR frequency by >110 kHz and that the finest tuning amount at 2K is <<10 Hz.

TUNER PROTOTYPING

The target RF frequency of the HWR (geometrical $\beta = 0.12$) is 162.5 MHz at a temperature of 2K. The slow frequency tuner ought to provide at least 80 kHz tuning range. In this design, we aim for a tuning amount of up to 200 kHz, which will give an adequate margin for the HWR frequency control. The tuner design has been well described in references [5-6].

The Cryogenic Stepper Motor

We adopted a Phytron cryogenic stepper-motor (VSS UHVC-X0) with a 1:100 harmonic drive gearbox [7]. The motor has 200 steps or 2,000 micro-steps per revolution; taking the gear ratio into account, it will be 20,000 steps or 200,000 micro-steps per revolution. A drive screw with 1/2nd- 20 threads is used in the prototype tuner. In the design [5], four revolutions from the output of the gearbox will tune the cavity by ~ 200 kHz, i.e. 2.5 Hz/step (0.25 Hz/micro-step). It should be pointed out that this resolution is the average number of the entire travel range; it will not be perfectly linear over the full tuning range. The motor driver adopted is from GalilTools [8] with a necessary modification to cut off holding currents. With this modification, the driver can power the stepper-motor without causing extra heating of the motor when not running.

Force Measurement on the Scissor Section

The calculation in the tuner design [6] shows that the output force from the scissor section ought to be larger than 300N to tune the HWR over the full range. A force measurement of the scissor section has been setup as shown in Fig. 1 (right). The output torque of the cryogenic stepper motor at its maximum current (2.5A) is 350 mN·m. After the gear box, the torque is amplified 100 times i.e. 35 N·m. We used a torque wrench to drive the shaft and measured the scissor section output force via a force sensor. Since the output force is also related to the angle of the scissor section, we measured the force by turning the shaft 1.25-2.75 turns and 3-4 turns respectively. The results, depicted in Fig. 1 (left), indicate that the maximum motor-gear-box torque (35N·m) can generate more than sufficient force to tune the cavity.

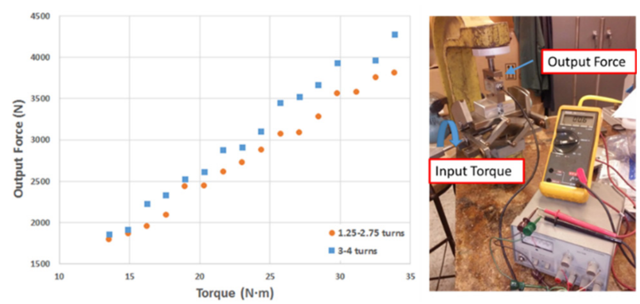

Figure 1: Input torque vs. output forces on the scissor section (left); the measurement set-up (right).

Long-Term Tests and Cold Tests

The tuner ought to be operated for 20 years. We assume the cryomodule will be warmed up at most twice a year, i.e. 40 thermal cycles in the tuner's lifespan, which would require the tuner to travel up to the full tuning range (200 kHz). Since the cryomodule will be operated stable at 2K, the tuner is assumed to be operated only twice a day to compensate small frequency drifts of the cavity. We therefore assumed there will be an additional ~730 sub-cycles

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† mg574@cornell.edu.

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per year, which each require covering 10 bandwidths of the cavity, i.e. ~800 Hz. Therefore, for the purpose of the long-term testing, we assumed that there are 80 cycles of the full tuning range, and each cycle has 365 sub-cycles for tuning 800-1000 Hz. We programed a Matlab code to control the tuner operation following this protocol during this long-term test. The setup of the long-term tests are shown in Fig. 2 (left). In the test, we used a spring load to simulation the force load from the HWR during tuning, as well as employed a regular stepper motor that can output the same torque level as the cryogenic motor.

After successfully completing the long-term tests, we immersed the long-term test set-up in a liquid nitrogen bath (77K) for a cold test, as is depicted in Fig. 2 (right). The purpose of the cold test was to confirm that the scissor section is not binding at low temperatures. We tested the set-up for about 80 cycles without issues.

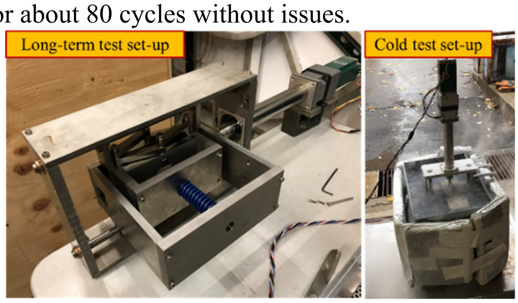

Figure 2: The set-up of the long-term test (left); the set-up of the cold tests (right).

TUNER CRYOGENIC TEST

Tuner Setup

In the tuner cryogenic test, the tuner was mounted on a prototype HWR (HWR-2); a reservoir had been installed in the test insert allowing liquid helium to be filled only into the HWR-2 helium tank as is shown in Fig. 3 (left). Since the tuner motor has magnets in it, it has to be wrapped with magnetic shielding to reduce flux trapping in the HWR walls during cool down; a copper stripe thermally connected the motor to the helium tank to cool the motor avoiding overheating, as is shown in Fig. 3 (right). The maximum working current of the motor had been set to 2.5A to obtain the maximum output torque.

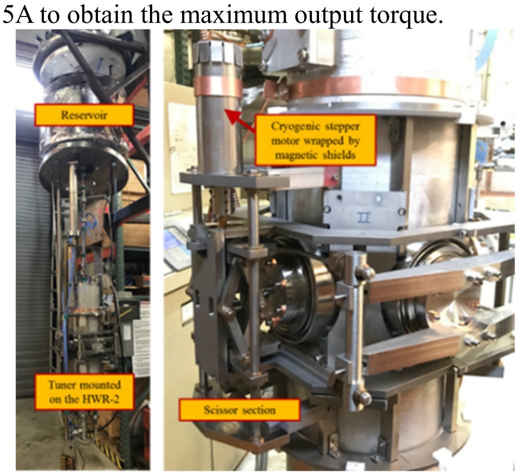

Figure 3: The HWR-2 with the tuner mounted on the test insert (left); detail photography of the tuner (right).

Tuner Test and Results

The tuner cryogenic test had three cool-downs. In the first cool-down, the cavity was not able to be cooled down to 4.2K; the lowest temperature we reached in the test was ~26K. We tested the tuner at ~110K. The tuner only turned a bit more than 2 turns on the drive screw before hitting a hard limit. In this run, the tuner shirted the frequency by a maximum of -80 kHz. After removing the interference causing the hard limit, a second cool-down was done in which liquid nitrogen was used to pre-cool the cavity. In this cool-down, the cavity reached ~20K. The tuner was tested around 50-60K. Again, the tuner could not be turned more than 2 turns and only decreased the frequency by ~50 kHz. It was later determined that the limit was due to the maximum motor current set too low during this test to output sufficient torque needed to turn the tuner beyond the 50 kHz point.

In the third cool-down, extra precooling was added, and the maximum motor current was set to 2.5A. In this cool-down, we successfully cooled the cavity down to 4.2K at which we ran the tuner for more than 5 turns on the drive screw without hitting any limits. We turned it backward after reaching this point. After the 4.2K test, we set the tuner to the 3rd turn position, fully filled the LHe reservoir, and pumped the HWR down to 2K. When the temperature reached 2K, we did a 2K hysteresis measurement which started from the 3rd turn position. We turned the tuner 1 turn more and then went back to the neutral position. The results at 2K and 4.2K, depicted in Fig. 4, show that the maximum tuning range during these cryogenic temperatures was 110 kHz. The curves at 2K is uniformly shifted above the 4.2K curve because the 4.2K to 2K cool-down caused the cavity frequency to increase ~12.73 kHz (due to the change in LHe pressure). The curves are very smooth and consistent for each forward and backward running. The smallest tuning amount that was resolvable during this test was limited by microphonics to ~10Hz.

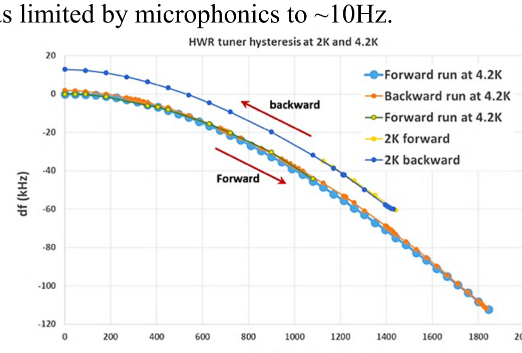

Figure 4: Hysteresis measurement at 2K and 4.2K.

The resolution and turn hysteresis of the tuner were tested at 2K, with results shown in Fig. 5, when the tuner was at the tuning angle of ~1200°. The smallest tuning amount used during this test was <10Hz. For the turn back performance checking, the tuner switched direction at the point A, D, and E. The start point and point A should be disregarded, since they were measured immediately after cooling down from 4.2K to 2K, which did build up small

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Table 1: Summary of the HWR-1 frequency in the vertical tests. All frequencies are given in units of MHz.

Frequency (MHz)	Simulation (IBS)	HWR-1 Bare-cavity	Δf Simu. –bare cavity	HWR-1 Dressed-cavity	Δf Simu.– dressed cavity
2K	162.600	162.664	-0.064	163.104	-0.504
4.2K	NA	162.646	NA	163.088	NA
Room temp.	162.310	162.382	-0.072	162.820	-0.510
After 150um BCP	162.314	162.328	-0.014	NA	NA

Table 2: Summary of the HWR-2 frequency in the vertical tests. All frequencies are given in units of MHz.

Frequency (MHz)	Simulation (IBS)	HWR-2 Bare-cavity	Δf Simu. –bare cavity	HWR-2 Dressed-cavity	Δf Simu.– dressed cavity
2K	162.600	162.590	-0.010	163.597	-0.003
4.2K	NA	162.500	NA	163.587	NA
Room temp.	162.310	162.325	-0.015	162.329	-0.019
After 150um BCP	162.314	162.316	-0.002	NA	NA

Table 3: Summary of the HWR-2 frequency in the tuner tests. All frequencies are given in units of MHz.

Frequency (MHz)	1st cool-down	2nd cool-down	3rd cool-down
2K no tuning	NA	NA	162.433
4.2K no tuning	NA	NA	162.420
Room temp. cable tight	162.216	162.239	162.210
Room temp. cable loose	162.319	162.318	162.314

additional stresses, which were released after the first change in tuning direction (point A). After releasing this stress, the typical hysteresis Δf is ~20Hz (e.g. between the point C and F). The measured tuning resolution and the hysteresis are small enough for the HWR operation with a cavity bandwidth of ~80Hz [9] at 2K.

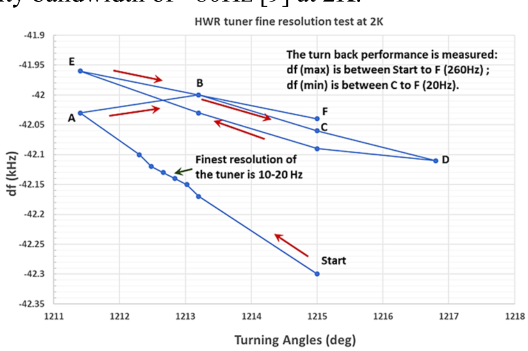

Figure 5: Tuner resolution and hysteresis performance.

During the pumping from 4.2K to 2K, we measured cavity frequency vs. pressure. The data fitting shows that df/dp is -15.58 Hz/Torr, as is shown in Fig. 6.

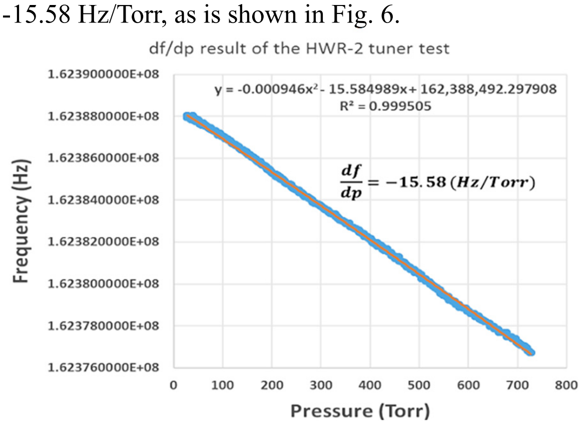

Figure 6: HWR df/dp measurement result.

FREQUENCY TRACKING

As frequency tracking is very important to achieve the target frequency in cryomodule operation, we measured the HWR frequency at each step. Table 1 and 2 summarize the measurement results during vertical tests of HWR-1 and HWR-2 respectively, and Table 3 lists the frequency information from the tuner test.

CONCLUSION

A new prototyping HWR tuner has been successfully designed, fabricated and tested at Cornell. We performed long-term tests at room temperature and cold tests in a liquid nitrogen bath (temperature 77K) to optimize the tuner mechanical structure prior to the final cryogenic (4.2K-2K) testing of the tuner on one of the HWRs. During the tuner cryogenic tests, the frequency hysteresis curves were measured at temperature 4.2K and 2K, demonstrating that the tuner can shift the HWR frequency by about 110 kHz and that the finest tuning amount at 2K is <10 Hz. The df/dp of the HWR-2 measured in the test is 15.58 Hz/torr, which can give a reference for the further cavity mechanical optimization.

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