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FRIB TUNER PERFORMANCE AND IMPROVEMENT*

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Abstract

The Facility for Rare Isotope Beams (FRIB) is under construction at Michigan State University (MSU). The FRIB superconducting driver linac will accelerate ion beams to 200 MeV per nucleon. The driver linac requires 104 quarter-wave resonators (QWRs, β = 0.041 and 0.085) and 220 half-wave resonators (HWRs, β = 0.29 and 0.53). The cryomodules for β = 0.041, 0.085, and 0.29 have been completed and certified; 38 out of 49 cryomodules are certified via bunker test (as of August 2019). The QWRs have a demountable niobium tuning plate which uses a warm external stepper motor. The HWRs use pneumatically-actuated bellows. Progress on the preparation and performance of the tuners is presented in this paper, along with improvements made to ensure that the resonators meet the frequency requirements.

INTRODUCTION

Frequency tuning characteristics for the FRIB resonators are summarized in Table 1. The FRIB half wave resonators (HWRs) use a pneumatic tuner [1, 2]. As shown in Fig. 1, the tuner is actuated by a bellows which expands and contracts with changes in helium gas pressure. The bellows is linked to a frequency-sensitive area on the cavity (the beam port cups) such that when the helium gas pressure changes, the cavity frequency changes. Bunker testing has shown that stable control can be achieved for single cavities over a span of several hours. Long term testing of multiple HWRs is planned in the next few months.

Table 1: FRIB Frequency Tuning Characteristics

Type	**QWR**		**HWR**	
Deformation	Bottom plate		Beam port cups	
Actuation	Stepping motor		Pneumatic	
Force	±150 lbs		1,000+ lbs	
Frequency	80.5 MHz		322 MHz	
β	**0.041**	**0.085**	**0.29**	**0.53**
Range (kHz)	20	50	62	39

The FRIB quarter wave resonators (QWRs) have a demountable bottom flange with a tuning plate attached. A similar tuner design was used successfully for the MSU reaccelerator [3], though improvements were made to the control system for FRIB. As shown in Fig. 2, the tuning plate has a mechanical link to a stepping motor for actuation. The stepper motor is outside of the cryomodule for ease of maintenance. Most cavities installed in the linac can be tuned by a low-cost stepper motor which provides up to 150 lbs of linear force. Additional space is provided for a warm piezo tuner, which may be added in the future to mitigate microphonics by cancelling disturbances [4].

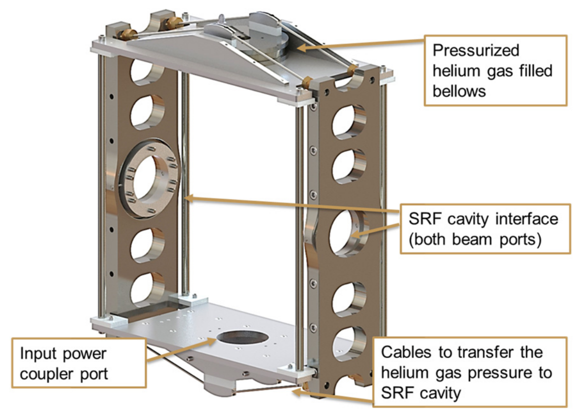

Figure 1: Isometric view of the pneumatic HWR tuner.

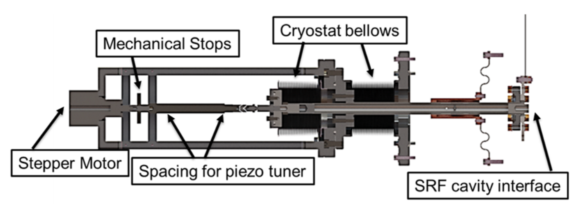

Figure 2: Rotated sectional view of the QWR tuner.

The FRIB team worked with suppliers to develop coarse tuning strategies during the manufacturing steps of the resonators. As a result, the suppliers could ship the resonators within a specified frequency range. During the process workflow to prepare the resonator for installation in the cold mass, frequency data was collected and reviewed before proceeding to the next step.

FREQUENCY CONTROL AND IMPROVEMENTS

The cavity certification test in the vertical test area (VTA) is the final quality assurance check before a resonator is installed onto the cold mass string. One criterion for acceptance is the frequency, which is measured at the operating temperature (~2 K). Statistics were gathered with pre-production resonators on the frequency shift for each preparation step, including the shift between the last room temperature bench measurement and the 2 K test. Some of the shifts are given in Table 2 (“installation” includes attachment of the input coupler and tensioning of the HWR tuner). An unexpected frequency shift may indicate a problem in one of the preparation steps.

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Table 2: Frequency Shifts (kHz) During Cavity Preparation

β	0.041	0.085	0.29	0.53
Chemical etching	−10	+14	−152	−151
Heat treatment	0	0	82	74
Cool-down	138	135	497	480
Installation	−10	−10	−88	**−60±20**

QWRs

For the QWRs, differential etching [5, 6] in the final preparation steps can tune accurately up to ±50 kHz. After the 2 K test, the tuning range is checked at room temperature. Some cavities required additional differential etching after the test. Smaller frequency adjustments (±10 kHz) can be made after 2 K testing via plastic deformation of the tuning plate.

Frequency tracking plots for the QWRs are shown in Fig. 3. The average values are shown in Table 2. Except for some early series resonators, the consistency in the frequency shifts for each step is relatively good. Reworks for frequency were fairly common in the early production stages, usually requiring repetition of some preparation steps and repeat 2 K testing. The reworks became less frequent once the processes were better understood.

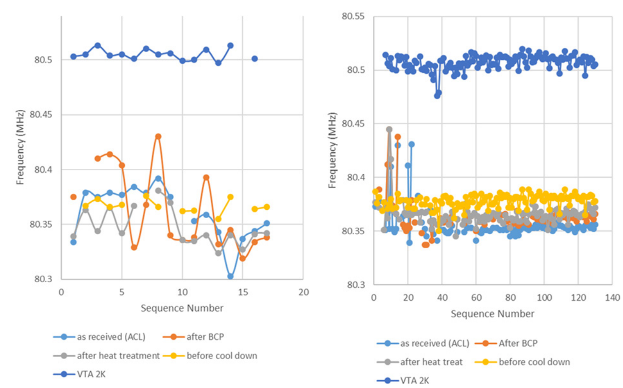

Figure 3: Frequency at various steps for β = 0.041 QWRs (left) and β = 0.085 QWRs (right). Horizontal axis: cavity sequence number.

During QWR production, measurements showed that the bellows used in the link of the tuning plate to the external actuator assembly was too stiff. Reducing the bellows stiffness increased the tuning range and reduced the number of frequency reworks. This is apparent in Fig. 4: some of the resonators installed in the linac have the older stiffer bellows with less overall tuning range.

In the first bunker tests for β = 0.041 cryomodules, the frequencies were lower than expected. The vacuum load on the external bellows is the source of the offset, as it adds approximately 100 lbs to the tuner. Plastic deformation of the tuning plate after cryomodule warm-up allowed us to shift the center enough so that the desired frequency could be reached with the small stepper motor. The deformation was done for before installation in the tunnel.

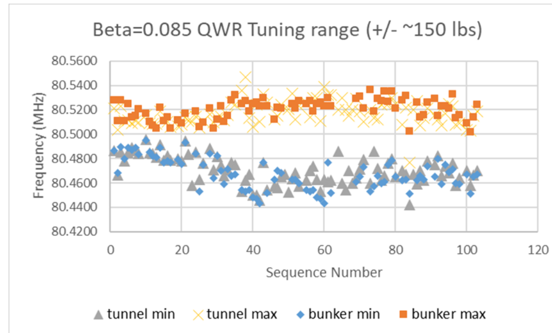

Figure 4: FRIB β = 0.085 QWR tuning ranges in the cryomodule bunker test and in the tunnel (horizontal axis: cavity sequence number).

Commissioning of the QWR linac provided additional experience with the tuners. After cool-down in the tunnel, the QWRs that were near the edge of the tuning range did not have good control in the 4.5 K bath [7]. Replacing the small stepping motor with a larger motor (Fig. 5), made the control stable for five QWRs. Though a trip from a tuner slip is a fairly rare event in bunker tests, long RF operation shifts with 104 QWRs registered several QWR trips per shift. Replacing the stepping motors on the cavities which had tuner phase jumps, even in cases with no tuning range issues, is so far a successful recipe to eliminate trips from tuner slips. At present, low-power tuning range measurements are done on each resonator before high-power operation.

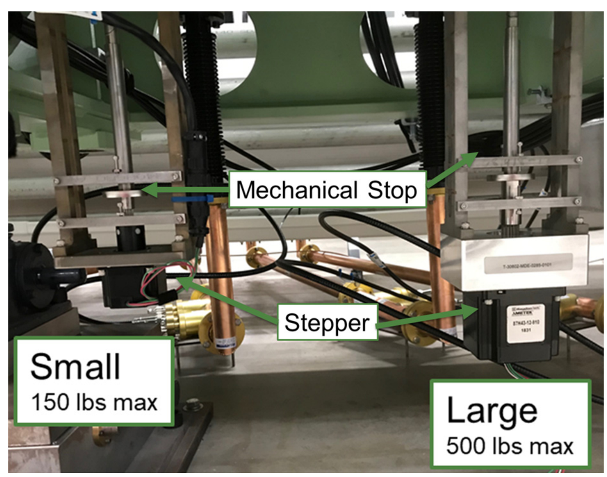

Figure 5: QWR tuner actuator upgrade.

HWRs

Frequency tracking plots for the HWRs are shown in Fig. 6. For FRIB HWRs, etching is used to achieve final frequency, but, the etching can only lower the frequency (unlike the QWR case where the frequency can be changed in both directions). The frequency shift from etching is limited to make sure the wall thickness remains adequate. If the frequency is too low, TIG tuning [8] is used to increase it; TIG tuning can increase the frequency by up to about 60 kHz. When a shift is needed beyond the TIG tuning range, plastic deformation is used [9]. The deformation is achieved by "plunger tuning" the niobium

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wall of the HWR where it is exposed by the helium return port on the outer titanium jacket. Thus plunger tuning can be done without removal of the helium jacket. It can be done after the 2 K test, during cryomodule assembly, or after the cryomodule bunker test.

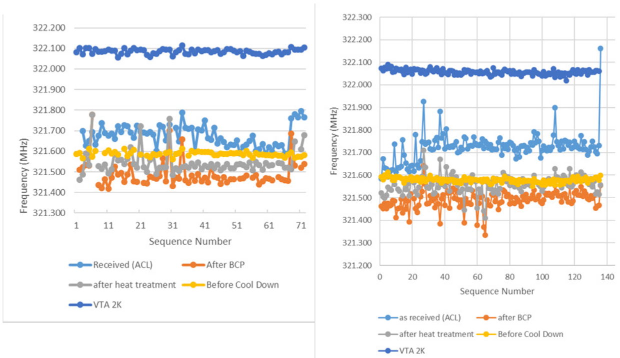

Figure 6: Frequency at various steps for β = 0.29 HWRs (left) and β = 0.53 HWRs (right). Horizontal axis: cavity sequence number.

The tuner gas pressure required to tune the β = 0.53 HWR to 322 MHz is imperfectly correlated with the frequency measured in the VTA 2 K test, as illustrated in Fig. 7. The spread in the required pressure is about 15 psi, which is half the desired pressure range. Table 2 highlights the uncertainty in the frequency shift during cryomodule assembly, where the uncertainty is larger than the average measured tuning range in Table 1. The variation in the tuning sensitivity, which ranges from −1.1 to −1.5 kHz/psi, accounts for some of the uncertainty. However, inconsistencies in the frequency shift during the final assembly of the HWR tuner components account for most of the spread, and led to two nonconforming HWRs during bunker testing. Additionally, several β =0.53 HWRs needed additional tuning after the tuners had been assembled onto the cold mass string.

The β = 0.29 case was more favourable than the β = 0.53 case. The β = 0.29 HWRs have 50% larger dynamic tuning range relative to the β = 0.53 HWRs and better repeatability of the frequency shift during tuner assembly. The β = 0.29 HWRs had fewer frequency reworks and no non-conformances in bunker tests.

The large uncertainty related to the assembly and tuning sensitivity for the β = 0.53 HWR lead to a small acceptance window. In early production, achieving an acceptable VTA frequency required multiple reworks. Adding a bench tuning range check before the final etch reduced the reworks. By comparing warm and cold tuning range measurements showed that the tuning sensitivity (frequency change per unit change in bellows pressure) does not change with tuner reassembly. There is a reduction in the tuning sensitivity due to cooling down to cryogenic temperatures. Therefore, the bench measurement cuts the uncertainty about the sensitivity, reducing the frequency-related reworks after testing.

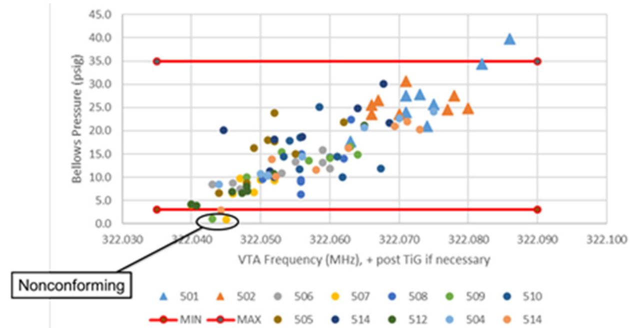

Figure 7: Required pneumatic tuner pressure (for operation at 322 MHz) as a function of measured VTA frequency for β = 0.53 HWRs.

CONCLUSION

The frequency tolerances during fabrication and surface preparation of FRIB superconducting cavities depend on the repeatability of the steps that cause frequency shifts as much as the dynamic tuning ranges and in-process tuning steps. Frequency data collected during resonator preparation steps lead to improvements and better process control. Due to the large scale of resonator production (340 resonators, 4 resonator types), detailed record-keeping and good communication between teams was required. The tuners were validated in integrated tests and cryomodule bunker tests; nevertheless improvements in the QWR tuning systems were still needed after initial linac commissioning. Commissioning of the HWR tuners in the FRIB linac is forthcoming.

ACKNOWLEDGEMENT

The successful cryomodule certification tests and linac commissioning would not have been possible without the contributions of Sergey Stark. Sergey led the campaign to integrate the tuning systems to the FRIB cryomodules until his untimely passing in 2018. We acknowledge the work he did to ensure smooth performance of the HWR tuners and to develop the simple method to upgrade the QWR stepper systems.

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