FREQUENCY MANIPULATION OF HALF-WAVE RESONATORS DURING FABRICATION AND PROCESSING*

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Abstract

Argonne National Laboratory is developing a superconducting resonator cryomodule for the acceleration of 2 mA H$^-$ beams from 2.1 to 10.3 MeV for Fermi National Accelerator Laboratory's Proton Improvement Plan II. The cryomodule contains 8 superconducting half-wave resonators operating at 162.500 MHz with a 120 kHz tuning window. This paper reviews the half-wave resonator fabrication techniques used to manipulate the resonant frequency to the design goal of 162.500 MHz at 2.0 K. This also determines the target frequency at select stages of resonator construction, which will be discussed and supported by measurements.

INTRODUCTION

Argonne National Laboratory (ANL) has designed and is now fabricating a half-wave resonator (HWR) cryomodule for the Proton Improvement Plan II (PIP-II) Injector Test (PIP2IT) at Fermi National Accelerator Laboratory (FNAL) [1, 2]. The HWR cryomodule contains 8 HWRs and 8 SC solenoids, with integrated *x-y* steering and return coils, for the acceleration of a ≥2 mA H$^-$ beam from 2.1 to 10.3 MeV. This HWR cryomodule is positioned immediately after the normal conducting radio-frequency quadrupole (RFQ) accelerator in the proposed 800 MeV linac. This linac will replace the existing 400 MeV linac as part of the PIP-II project [3, 4, 5].

Figure 1 shows the major sub-assemblies which comprise a HWR. Figure 2 shows a finished HWR. The HWRs are fabricated from bulk niobium and have no demountable joints for tuning. Because all of the formed sections are Electron Beam Welded (EBW) into the final resonator assembly the dimensions of the parts must be properly sized to attain the desired room temperature frequency of 162.581 MHz. This is a precursor to the final 2.0 K resonant frequency being 162.500 MHz. Final fine tuning is accomplished via plastic deformation of the cavity at the beam ports after the HWR assembly is welded, the helium jacket is installed and all surface polishes are finished.

In the next section the target frequency at various stages of cavity implementation are described and results are presented. This is followed with a brief review of the impact which this tuning procedure has on the cavity performance at 2.0 K and a few concluding remarks.

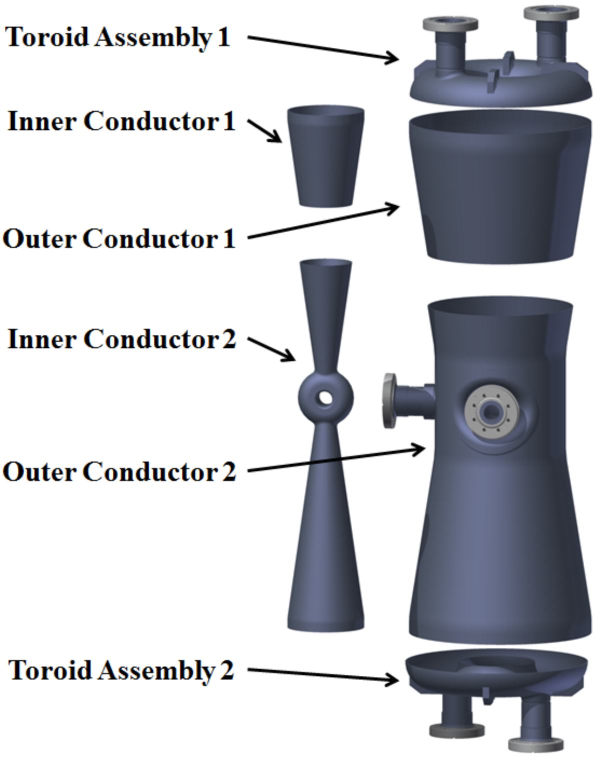

Figure 1: The major sub-assemblies which comprise a half-wave resonator. The parts shown are assembled with indium wire in all of the joints to determine the resonant frequency during the final stages of fabrication. After the frequency measurements the assembly is welded.

Figure 2: Left, two half-wave resonators in the cleanroom after final electron-beam welding. Top right, a half-wave resonator immediately prior to the final electron beam welding. Bottom right, a finished half-wave resonator. The HWR end-to-end length is 48 inches at room temperature.

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FREQUENCY TUNING

Resonator tuning starts with the individual HWR subassemblies (Fig. 1) prior to the final EBW steps. Each part is manufactured with its overall length longer than is required. The parts are held together by fixtures with indium wire placed in all joints and the resonant frequency is measured, Fig. 3. This measurement determines the material removal necessary to bring the HWR onto the target frequency and the parts are trimmed using wire Electric Discharge Machining (EDM). By symmetrically trimming both sides of the HWR inner and outer conductors a sensitivity of +288.4 kHz/mm was expected. This was achieved in practice with the measured sensitivity being within ±15 kHz/mm. Most of this uncertainty is due to the frequency measurement not the trim cuts.

The final EBW results in the the largest frequency shift, +337 kHz, and a large uncertainty. The uncertainty is due to variations (≤0.030”) in the weld shrinkage which can be compounded if extra EBW passes are needed. Further shifting the HWR frequency are the installation of the helium jacket, chemical polishing, evacuation, cool down, and the intrinsic detuning of the slow tuner. The frequency of 6 HWRs has been measured throughout the entire tuning procedure and the target frequency results are summarized in Table 1.

Here a modified version of the ANL pneumatic tuner [6] will be employed with a maximum design force of ~10,000 N squeezing the cavity between the beam ports, corresponding to a ±60.0 kHz shift in the cavity resonant frequency. The slow tuners are mechanically limited to this tuning force to prevent excessive plastic deformation of the HWRs at room temperature. ANSYS [7] simulations show the niobium locally yielding with an applied tuner force of 2,500 N and the 304 stainless steel helium jacket locally yielding with a 7,500 N force at room temperature (293 K), Fig. 4.

After fabrication is finished the largest uncertainty in mapping the cavity target frequency is the frequency shift due to electropolishing (EP). Simulations were carried out with Computer Simulation Technology’s (CST) Microwave Studio [8] which modelled a uniform material removal from the cavity surface. These calculations resulted in an expected frequency shift of -66 kHz for a uniform 130 μm EP. In practice this was not achieved and the total frequency shift was measured to be +199 kHz in the first HWR processed. Here the weight of niobium removed was equivalent to that expected for a uniform removal of 130 μm. This indicates a greater amount of material removal in the high electric field region of the HWRs, a faster etch rate at the beam ports, which was accounted for in the other HWRs.

After all fabrication and processing is finished the final tuning step is a plastic deformation of the HWR. The HWR is either plastically squeezed or stretched at the beam ports to achieve the target room temperature frequency. All of the HWRs have been plastically tuned in this manner by ±200 kHz, which is less than 0.5 mm of plastic set per tuning procedure.

Figure 3: HWR sub-assemblies clamped together for resonant frequency measurements. The drive and pick-up probes are weakly coupled to avoid perturbing the resonant frequency.

Table 1: Target HWR Resonant Frequency at 20^0C and 40% Relative Humidity during Fabrication and Operation

Cavity Status Description	Target Frequency (MHZ)
2.0 K with Slow Tuner	162.500
2.0 K without Slow Tuner	162.560
4.2 K	162.573
293 K, Under Vacuum	162.405
After Final 20 μm EP	162.335
After Final 130 μm Polish	162.389
After Helium Jacketing	162.588
After Final Nb EBW	162.581
After wire EDM Trim	162.244

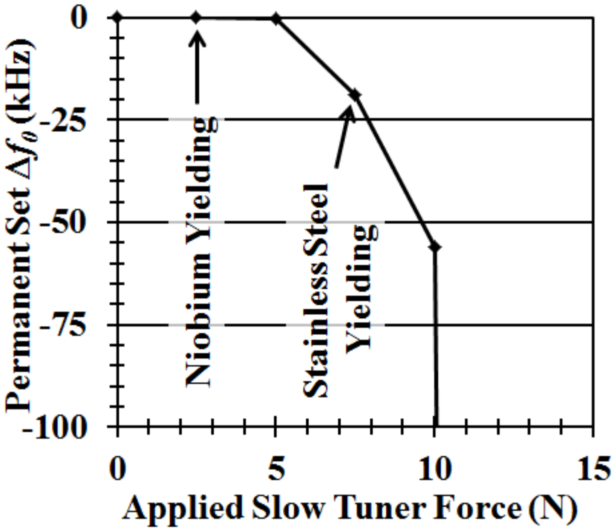

Figure 4: HWR frequency shift due to plastic deformation of the slow tuner operating at room temperature, 293 K.

2.0 K CAVITY PERFORMANCE

The frequency shift of the HWRs between 293 K and 2.0 K was measured by assembling the resonator in a configuration similar to that found in the cryomodule, Fig. 5. In this configuration the cavity is supported from the bottom, a vacuum pumping spool is attached to a toroid port, and a slow tuner is installed on the cavity. The HWR frequency was measured at room temperature prior to the start of cool-down and again once the system was in equilibrium at 4.2 and at 2.0 K. Nominally the HWR frequency shift was measured to be +220 kHz. ANSYS [7] modelling gives a frequency shift of +167 kHz, 53 kHz less than the measured value. This may be due to the absence of kinematic mounts supporting the HWR or due to the HWRs having a slightly different structure than modelled.

In parallel with measuring the HWR frequency shift due to 2.0 K cool down the HWRs radio-frequency performance was measured. Figure 6 shows the data from these measurements for the 6 HWRs tested to date. The cavities were operated in the continuous wave mode with unity coupling at all accelerating gradients shown. There was no observable field emission, next to the test cryostat on the inside of the test cave, up to peak surface electric field of 70 MV/m for all tests. Three of the six cavities had no measureable field emission up to 90 MV/m. At the nominal design gradient of 9.7 MV/m (2 MV/cavity) at 2.0 K the measured RF losses are ≤ 1 W for all cavities.

SUMMARY

The HWR tuning procedure and frequencies presented here outline the Argonne method of attaining the desired resonant frequency at 2.0 K. This method is applicable to other cavities and similar procedures have been carried out previously with two sets of quarter-wave resonators [9, 10]. One advantage of this method is the use of plastic deformation of the cavity for the final fine tuning of the HWRs. This avoids the added man-power requirements of other methods which rely on differential etching and may degrade the cavity performance.

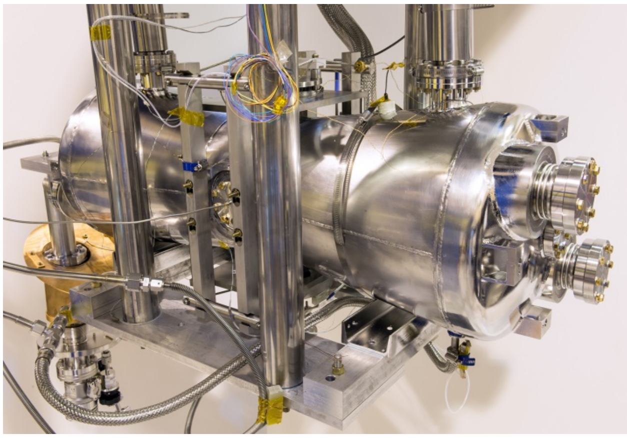

Figure 5: A half-wave resonator ready for 2.0 K testing.

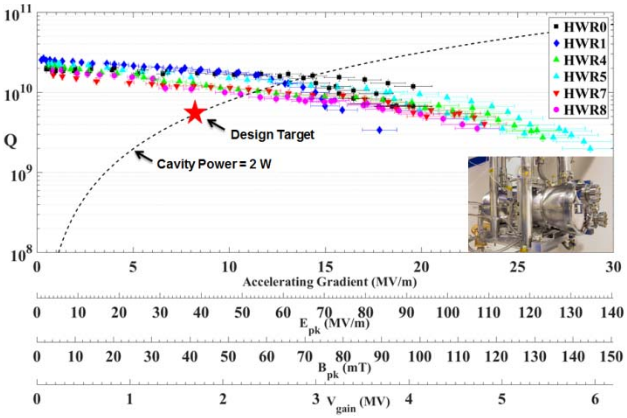

Figure 6: Measured 2.0 K HWR performance.

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