FREQUENCY TUNING AND RF SYSTEMS FOR THE ATLAS ENERGY UPGRADE SC CAVITIES*

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Abstract

A new cryomodule with seven low-beta superconducting radio frequency (SRF) quarter wave niobium cavities has been designed and constructed as an energy upgrade project for the ATLAS accelerator at Argonne National Laboratory [1]. The technology developed for this project is the basis for the next generation superconducting heavy ion accelerators. This paper will discuss the methods employed to tune the cavities eigenfrequency to match the accelerator master oscillator frequency and the development of the RF systems used to both drive the cavity and keep the cavity phase locked during operation.

INTRODUCTION

The ATLAS Energy Upgrade Project includes a new cryomodule containing seven 109 MHz, β=0.15c quarter-wave superconducting cavities to provide an additional 15 MV voltage to the existing superconducting linac. The cavities are constructed so that there are no demountable joints. Due to the fact that all of the manufactured sections of the cavity are electron beam welded into the final cavity configuration, the dimensions of the parts prior to welding must be properly sized in order to achieve the final eigenfrequency demanded by the accelerator's Master Oscillator system. Also, in order to phase lock to the accelerator's Master Oscillator, two other systems are employed; a slow tuner system [2] is used to compensate for frequency shifts due to pressure changes, and a fast tuner system [3] is used to compensate for frequency shifts due to microphonics.

CAVITY TUNING DURING CONSTRUCTION

The individual cavity parts are formed and then electron beam (e-beam) welded into four sections. These four sections are illustrated in Fig. 1. They are the housing, the toroid, the center conductor and the dome. All four sections are manufactured with their length longer than needed. They will all be trimmed to length in increments so that in the end, the proper frequency will be achieved. The first step is to trim the dome and the toroid once, using Electrical Discharge Machining (EDM). This trim cut is to establish a square edge that will facilitate alignment to the housing and center conductor.

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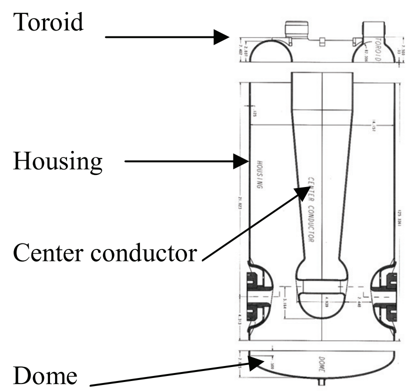

Figure 1: Four main cavity sections.

Several parameters must be known to determine what length the housing and center conductor will be trimmed to. For example, when the individual pieces are e-beam welded together, shrinkage of the niobium occurs that results in a frequency shift. This frequency shift must be accounted for in the sizing of the cavity parts. In addition, when the parts are electro-polished [4] the removal of the niobium results in a frequency shift which also must be accounted for. Table 1 lists the desired frequency at 4.5K and other parameters that must be known to achieve the final sizing results.

The four sections are assembled in a fixture which keeps them alligned and clamped together. indium wire is compressed between each clamped joint of this assembly.

Table 1: Development Parameters

Master Oscillator Frequency (for *B* =.15c)	**109125.0**	**kHz**
Slow Tuner Half-range	+20	kHz
1-shot hydraulic tuning	+/-20	kHz
ΔFreq / ΔElectro-Polish (uniform)	282.2	kHz/mm
ΔFreq / ΔEP(Dome & Toroid)	1078.9	kHz/mm
ΔFreq / ΔPressure (Helium Jacket)	-9	kHz/atm
ΔFreq / ΔAIR (20C, 740 Torr, 40% Humid)	-34	kHz
ΔFreq / ΔT(293K - 4K)	-156	kHz
ΔFreq / ΔIndium wire .010" thick	-26	kHz
ΔFreq / ΔLength (center conductor)	-132	kHz/mm
ΔFreq / ΔLength (distance to dome)	30	kHz/mm

The indium is necessary to reduce the joint losses at RF frequencies. Fig. 2 shows the individual sections clamped together in the "birdcage" for a frequency measurement.

Figure 2: Parts clamped in *birdcage* for a frequency measurement.

Once the initial frequency is measured a calculation is made to determine how much to shorten the center conductor and the housing. The center conductor and the housing are assembled with a second jig that aligns the beam hole in each piece and centers the top of the center conductor in the housing. The assembly is then put on an EDM machine and one cut is made to both pieces simultainously. Fig. 3 shows the results of several trim cuts.

Figure 3: Trim cuts by EDM.

The process of clamping together all of the sections in the *birdcage* is repeated and then another trim cut is made to the center conductor and housing. This process is repeated until the desired, room temperature-clamped together frequency is achieved. Then the parts are electropolished and e-beam welded together to form a single assembled unit. Table 2 follows the frequency progression, working backwards from the cold frequency, to achieve the desired room temperature-clamped together frequency.

Table 2: Frequency Progression

Master Oscillator Frequency (for *B* =.15c)	**109125.0**	**kHz**
Final cold frequency (4.3K) *+20 kHz for ½ Slow Tuner Range*	109145	kHz
At room temperature under vacuum	108989	kHz
Vented to air	108966	kHz
Before EP (125 microns base, 187 DT&Nose)	108728	kHz
Before welding (.58 mm shrink/weld)	108669	kHz
Clamp-up state (including .010 thick crushed indium wire)	**108643**	kHz

This tuning method was applied to all seven cavities. The results are listed below in Table 3.

Table 3: Final tuning Results for all seven Cavities

	293K	**4.5K**
*1	109016.0	109165.9
2	108953.1	109137.0
3	108952.0	109137.7
4	108952.5	109142.9
5	108954.6	109137.2
6	108952.0	109136.3
7	108955.1	109140.8

*Note: cavity number 1 below, is a different design from the other six. Its slow tuner range is double that of the others so its resulting frequency is higher in order to bring it into the middle of the slow tuner.

Fig. 4 shows the slow tuner range for a cavity at 4.5 K. The red line indicates the frequency of the accelerator's Master Oscillator.

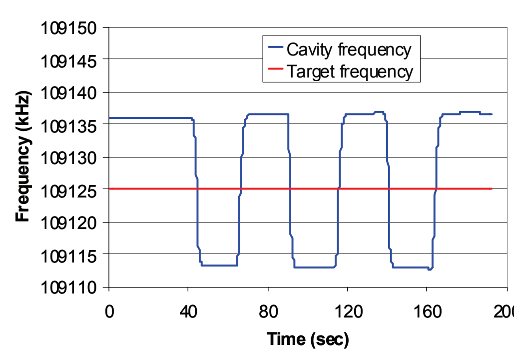

Figure 4: Typical slow tuner range measured at 4.5K.

RF POWER COUPLERS

Two types of RF power couplers were designed and tested on the quarter wave cavities. One coupler is an inductive coupler and the other is a capacitive coupler. Both coupler designs have a variable coupling strength with a stroke of about three inches. Fig. 5 shows a picture of each coupler.

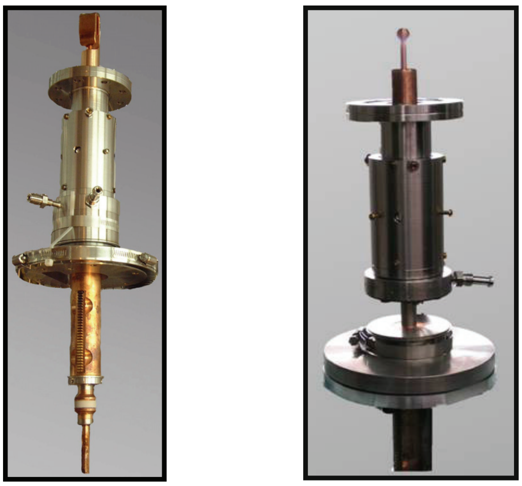

Figure 5: Inductive coupler on the left and a capacitive coupler on the right.

The coupler design for both types of couplers are very similar, the main difference being the probe tip. Fig. 6 is a cut-away diagram of the capacitive coupler and its features.

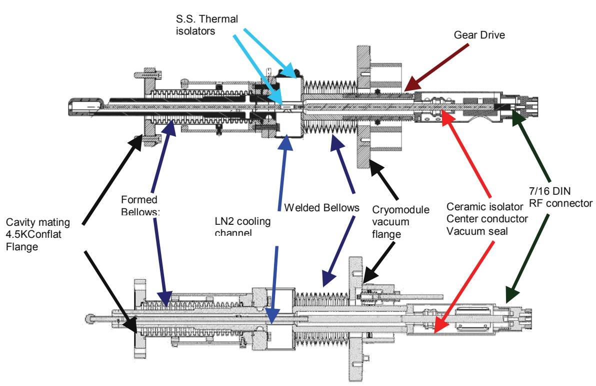

Figure 6: Design features.

Two tests were done on each probe. The two test conditions were the following. Test 1: the RF probe was fully inserted into the cavity resulting in an over coupled condition. Then approximately 600 Watts of RF power was applied to the coupler. Test 2: it was performed with each RF coupler in the critically coupled position. Then the field level of the cavity was set to approximately 9 MV/m. It must be noted that the coupling port on the cavity is located in an electric field region. To measure the power dissipation into the helium system for each coupler, a thermometer and a resistive heater were placed on the 4.5 K mating flange of the coupler and cavity. Thermometers were also placed on the 77 K intercept point and room temperature sections of the couplers. The test results show for the 600 W over coupled condition, that for both couplers the heating at the 77 K and 290 K sections were negligable. Measurements on the 4.5 K mating flange for each coupler was significantly different. Fig. 7 illustrates the heating results for all conditions. As expected the power into the helium system for the inductive probe was high. For the capacitive coupler in the critically coupled position the power into the helium system was in the 100's of milliwatts.

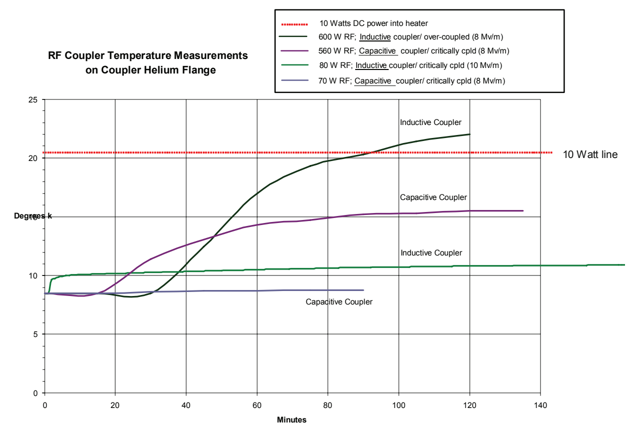

Figure 7: RF Coupler heating at the 4.5K flange.

CRYOMODULE 4.5K TESTS

Seven cavities were assembled in a clean room following clean assembly techniques. The cavity assembly was then mounted in the box cryomodule. The cavities were cooled down to 4.5K and the cavity subsystems were tested. Six of the seven cavities were brought up to high field levels, the seventh cavity was tested at low power only. Measurements were take on the slow tuner ranges, the fast tuner windows, cavity frequencies, microphonics, and peak accelerating fields. All subsystems functioned as designed and were within the specified performance parameters.

The frequency deviation due to microphonics is defined by a gaussian distribution. The measured sigma value for the frequency deviation on the cavities was measured at 1.05 Hz RMS. In order to phase lock a SC cavity a control window of at least 8θ is required. The fast tuner windows measured 35 to 45 Hz. This is well over the 8θ that is needed. Fig. 8 shows a plot of the the frequency deviation of a typical cavity and a plot of the fast tuner range as measured in a cavity.

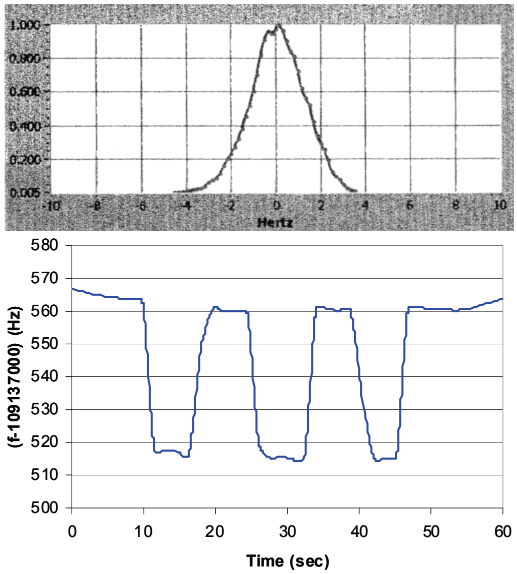

Figure 8: Top, measured frequency deviation from microphonics. Bottom, measured fast tuner window.

The field levels achieved are shown in Fig. 9 along with the field levels for each cavity as tested after production in an off-line test cryostat. Each cavity was High Pressure Rinsed (HPR) [5] after the initial off-line test, just prior to the cryomodule assembly. The HPR and more stringent clean assembly techniques accounts for the improvement of some of the cavities in the cryomodule tests displayed in Fig. 9.

Figure 9: Field level results.

CONCLUSIONS

The parameters that were developed and used to calculate the cavity sizing were successful. All of the 4.5 K cavities frequencies were correct.

The RF power couplers performed well, their coupling strengths were within the design specifications. The power dissipation tests demonstrated that the capacitive coupler is the preferable design for use on this type of cavity, though the inductive coupler will also work.

The microphonics as measured with the cryomodule operating on the helium refrigerator system is low. The fast tuner window is more than adequate to phase lock the cavities.

Finally, the field level performance is above the 8 MV/m operational requirement. The average field level of the six cavities is 12.1 MV/m, but when the fast tuner is employed the average field level is lowered to 9.2 MV/m. This limitation of the fast tuner is a subject for future development. We are planning to develop a new system to replace the reactive power fast tuner that is presently in use.

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