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FREQUENCY PRE-TUNING OF THE 166.6 MHz HOM-DAMPED SRF CAVITIES FOR HEPS

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Abstract

A higher-order-mode-damped 166.6 MHz β=1 quarter-wave superconducting cavity is being developed for the High Energy Photon Source. The frequency variation of the cavity in all the processes comprising of manufacturing, post-processing and cooldown to 4.2 K, should be strictly controlled due to the relatively small coarse tuning range. The step-by-step evolution of the cavity frequency was determined and the target frequency after fabrication was given. The pre-tuning scheme during fabrication was made in which the length of the inner conductor and the outer conductor are the free parameters for frequency pre-tuning while the cavity length is kept constant. The environment of the cavity in the cryomodule was considered in the analysis. Three bare cavities and one jacketed cavity were fabricated, post-processed and vertical tested with careful frequency monitoring. The measured frequencies were consistent with the predictions in each process.

INTRODUCTION

High Energy Photon Source (HEPS) is a 6 GeV 1.3 km storage ring light source with ultralow emittance. It is currently under construction in Huairou, Beijing and will be completed in 2025 [1]. A 166.6 MHz β=1 Superconducting RF (SRF) quarter-wave cavity has been designed as the main accelerating cavity for the storage ring [2, 3]. A proof-of-principle (PoP) cavity was previously developed for HEPS - Test Facility (HEPS-TF) project [4]. The cavity frequency was carefully monitored during the production, cavity treatment and vertical tests [5]. Based on the PoP cavity, a higher-order-mode (HOM) damped 166.6 MHz compact SRF cavity dressed with a helium vessel was subsequently designed and the first three cavities were subsequently manufactured [6, 7].

The resonant frequency of the 166.6 MHz cavity will change in the processes comprising of manufacturing, post-processing, assembly into the cryomodule and cooldown to 4.2 K. It should be characterized carefully as the frequency tuning range of this kind of cavities is relatively smaller than the elliptical cavity. The longitudinal length of the 166.6 MHz cavity was limited by the compact SRF cavity module design, which also posed a challenge for frequency pre-tuning. The frequency evolution was developed by electromagnetic-mechanical coupled simulations and analytical calculation, where previous experiences from the PoP cavity were also used. The pre-tuning scheme during fabrication was made on the basis of understanding the frequency variation. The length of the inner and outer conductors was proposed as free parameters for frequency pre-tuning. Three bare cavities were fabricated following the pre-tuning scheme and their frequency variations were monitored throughout the subsequent surface treatments and vertical tests. One bare cavity was then welded with a helium jacket, vertical tested, and is currently being assembled with the cryostat during which the frequency is under precise control.

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TARGET FREQUENCY

The target frequency of the cavity operating at 4.2 K in the cryomodule is 166.6 MHz. The cavity is evacuated to vacuum and immersed in liquid helium of 1.23 bar. The structure of the cavity with the liquid helium vessel is shown in Fig. 1. In the cryomodule, the end plate of the helium vessel near the small beam pipe is partially fixed (blue), and the four blocks around the helium vessel are limited to move only in a longitudinal manner (red). This support scheme is used in the following study.

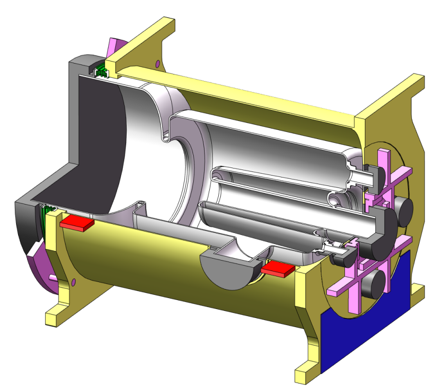

Figure 1: 166.6 MHz cavity dressed with the helium vessel.

Figure 2 shows the step-by-step frequency evolution from operation to the fabricated cavity before surface treatment. These values, expect for the case of surface treatment, were calculated by the thermal, electromagnetic and mechanical simulations by using CST and ANSYS codes. The tuner applies a pre-loading force to stretch the cavity during operation, and it will increase the cavity frequency by 25.5 kHz. The cavity frequency increases by 19.4 kHz when the 1.23 bar liquid helium pressure outside the cavity is converted to vacuum. When the cavity warms up from 4.2 K to 293 K, its frequency is reduced by 227 kHz because of the thermal expansion. Disconnecting the cavity from the cavity string containing HOM damper, gate valves, etc., in-

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creases the frequency by 10 kHz. The change of permittivity from vacuum to ambient air will reduce the frequency by 53 kHz. As for the surface treatment process, the cavity frequency will increase by 76 kHz after several buffered chemical polishing (BCP) and annealing treatment, according to the experience of the PoP cavity [5]. Finally, the cavity should have a frequency of 166.209 MHz after all the welding at standard ambient conditions of 20°C, 1 atm and 50% relative humidity. This provides a reference for the manufacturing process of the cavity.

f_0(MHz)	Δf(kHz)	T	Cavity inside volume	Cavity outside volume
166.600		4.2 K	Vacuum	1.23 bar LHe
	-25.5		tuning force → 6.4kN	
166.575		4.2 K	Vacuum	1.23 bar LHe
	-19.4		Pressure difference between inside/outside	
166.555		4.2 K	Vacuum	Vacuum
	-227		4.2 K → 293 K	
166.328		293 K	Vacuum	Vacuum
	10		dressed cavity string (damper, valve, ...)→bare cavity	
166.338		293 K	Vacuum	Ambient air
	-53		Vacuum → air	
166.285		293 K	Ambient air	Ambient air
	-76		BCP and Annealing	
166.209		293 K	Ambient air	Ambient air

Figure 2: Step-by-step evolution of the cavity frequency.

CAVITY FREQUENCY PRE-TUNING

The 166.6 MHz cavity consists of four components: left end-plate (LEP), outer conductor (OC), inner conductor (IC) and right end-plate (REP) as shown in Fig. 3. During fabrication, the frequency measurement setup is shown in Fig. 4. The components of the cavity are assembled by the support frame to ensure good RF contacts. The measured frequency is corrected for ambient temperature, atmospheric pressure and humidity. The frequency perturbation by the pickup antenna and by the preload on the support frame are also taken into account.

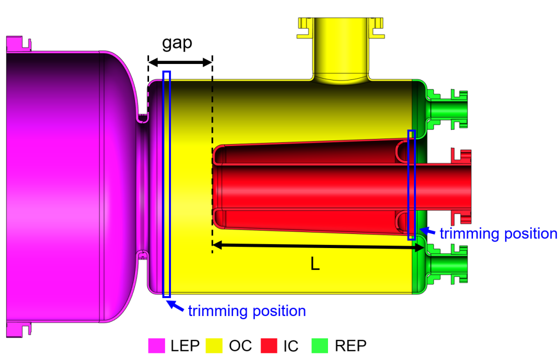

Figure 3: The components and the main geometric parameters of the cavity, as well as the trimming positions for cavity frequency pre-tuning.

When operating in the storage ring, five 166.6 MHz SRF cavities will be installed in the cryomodules of the same specification, and the difference in the lengths of the cavities is limited to 5 mm. In the PoP cavity, the accelerating gap length in Fig. 3 is the free parameter for the cavity frequency pre-tuning. The frequency variation corresponding to *gap* change of 5 mm is about 120 kHz when *gap* is about 120 mm, as shown in the simulation curve in Fig. 5. Frequency adjustment range by *gap* is relatively small. In contrast, the frequency is more sensitive to the length of the IC, i.e. *L* in Fig. 3, 363 kHz/mm shown in the simulation curve in Fig. 6. Moreover, the length of the IC does not affect the total length of the cavity. Therefore, the pre-tuning scheme is to trimming the IC and the OC so that the frequency reaches the target specified in the previous section, while the length of the cavity meets the requirements.

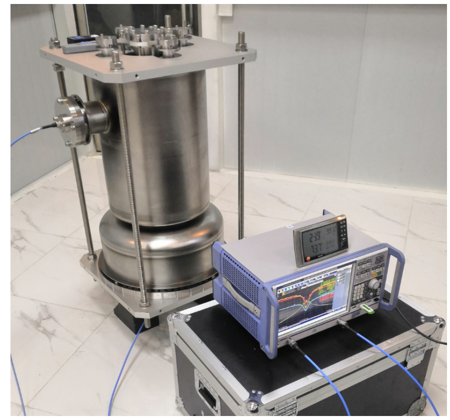

Figure 4: Frequency measurement setup.

The cone length of the IC was longer than the design value, and the left side of the OC also had a margin for trimming initially, as the trimming positions shown in Fig. 3. The following details the pre-tuning process.

Firstly, the resonant frequency of the cavity is measured before welding of the IC and the REP. If the frequency is below the target, it can be gradually approached by trimming the cone of the IC. Fig. 6 shows this process during the pre-tuning of the CAV#2 while no trimming was required at this process for CAV#1 and CAV#3. The initial measured frequency was 166.495 MHz and the corresponding length of IC was 405 mm. The working curve is obtained by moving up the simulation curve to intersect the initial measured point. The intersection of the working curve and the target frequency shows the amount of trim. So the IC was trimmed by 0.5 mm to increase the frequency to the target 166.725 MHz, considering the weld shrinkage and the dimension allowance of the rest parts.

Secondly, the three components IC, REP and OC were welded together. The cavity frequency was measured before and after each welding to monitor the evolution.

Thirdly, the frequency was reduced by trimming the left end of the OC to meet the target before welding the OC and LEP. In Fig 5, the OC of CAV#1 was trimmed by a total of 26 mm, and the frequency dropped by 752 kHz, approaching the target frequency of 166.219 MHz for consideration of the last weld shrinkage. Similar pre-tuning processes at gap of the cavities were also present in CAV#2 and CAV#3.

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The measured frequency variations were consistent with the prediction during pre-tuning.

Lastly, after all the welding is completed, the cavity could be stretched or compressed to a small extent, so that the cavity had a small plastic deformation to adjust the resonant frequency of the cavity if required. The deformation allowance was limited by a number of factors. For example, excessive deformation may affect the subsequent welding of the helium jacket and the assembly within the cryomodule.

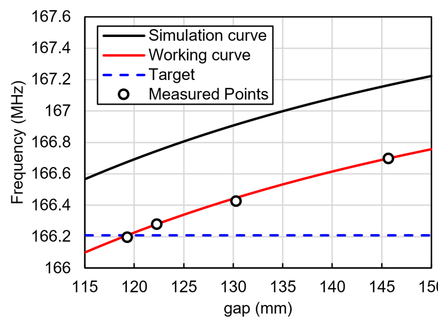

Figure 5: Frequency pre-tuning at gap.

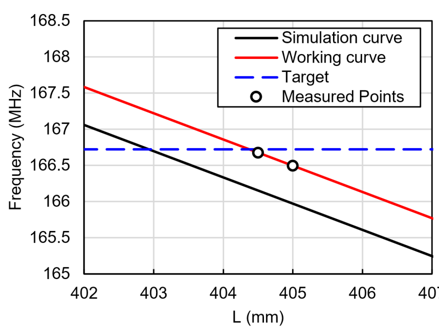

Figure 6: Frequency pre-tuning at inner conductor.

FREQUENCY VARIATION

The frequencies of the three 166.6 MHz cavities were carefully monitored during each process from fabrication to vertical tests, as shown in Fig. 7. The frequency of CAV#1 in 4K vertical test matched the target of 166.6 MHz. Then it was welded a helium jacket and vertical tested in 2 K, during which the frequency was 66 kHz lower than the target of 166.6 MHz. The frequency deviation was caused by the preload of the support frame in vertical tests, while it can be corrected by slightly stretching the REP, resulting in a deformation of approximately 0.2 mm. After assembling into the cavity string, the cavity frequency pre-tuning was accomplished by adjusting the preload force on the stiffeners installed on the small beam pipe and the end plate of the helium vessel, i.e. the pink stiffeners near the small beam pipe in Fig. 1.

The target frequency after fabrication for CAV#2 and CAV#3 was updated to 166.329 MHz according to the measured frequency variation of CAV#1 in the post-processing. The frequency of CAV#2 during 4K vertical test was measured to be 45 kHz higher than the target and it also can be corrected by compressing REP slightly. As for CAV#3, due to the machining defects on the IC in the production, the length of IC is approximately 1 mm smaller than the design value, so the measured frequency is more than 300 kHz higher than the target. It could not be compensated by shortening the gap within the cavity length allowance, so the frequency was reduced by REP shape correction before LEP welding. However, the consequent excess deformation affected the high-pressure rinsing. The cavity was adjusted back to the high-frequency geometry again before surface treatment. The frequency of CAV#3 in the vertical test was 155 kHz higher than 166.6 MHz, and it may subsequently be corrected by plastic deformation of the cavity.

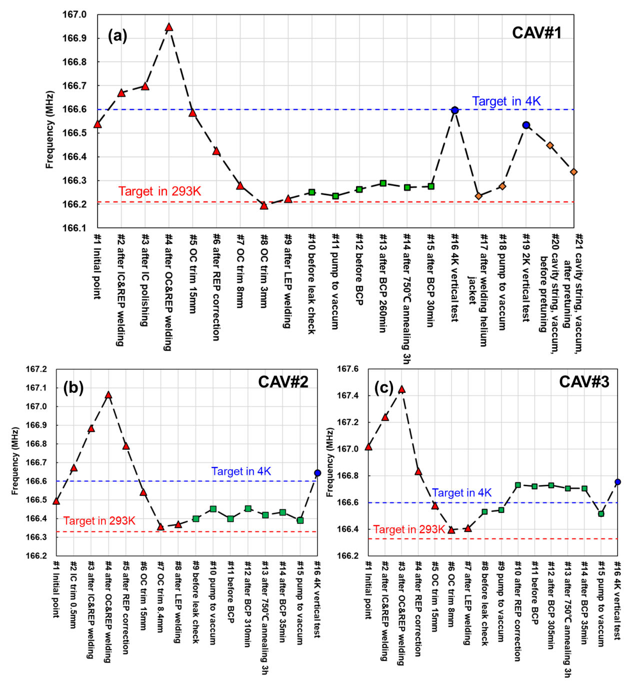

Figure 7: Cavity frequency evolution.

FINAL REMARKS

Frequency evolution of the 166.6 MHz HOM-damped SRF cavity dressed with the helium vessel from manufacturing to cooldown was determined by simulations and previous experiences of the PoP cavity. The frequency measurement target after welding was also determined. The pre-tuning method was proposed to accommodate the frequency evolution by trimming the inner and outer conductors. It serves as a guide for the fabrication of the cavity.

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