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FREQUENCY PRE-TUNING OF THE 166.6 MHz PROOF-OF-PRINCIPLE SRF CAVITY FOR HEPS-TF

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Abstract

A 166.6 MHz proof-of-principle SRF cavity has been designed for the High Energy Photon Source-Test Facility (HEPS-TF). The cavity is a β=1 quarter-wave resonator made of bulk niobium operating at 4.2 K. A pre-tuning scheme was made to accommodate the cavity frequency shift mainly due to manufacturing tolerances, the subsequent surface treatment and finally the cooldown process. To this end, the length of the cavity outer conductor was chosen as a free parameter for the pre-tuning. The cavity frequency was carefully monitored during the production, cavity treatment and vertical test. The measurement results agree well with our calculations. It is worth noticing that the pre-tuning method only involves one-time measurement of the cavity resonant frequency and its outer conductor length.

INTRODUCTION

High Energy Photon Source (HEPS) has been planned by IHEP to be built in Beijing suburb in the next few years. It is a 6 GeV, 200 mA light source with a kilometer-scale storage ring aiming for ultra-low emittance [1]. The fundamental RF frequency is 166.6 MHz while the high harmonic cavity is of 499.8 MHz [2]. Prior to its official construction, a test facility (HEPS-TF) was approved in 2016 to R&D key technologies. The current focus of the RF system is the 166.6 MHz superconducting cavity. A proof-of-principle (PoP) cavity has been subsequently designed, fabricated and vertical tested this year and reported in [2, 3].

The production of a 166.6 MHz PoP cavity requires several process steps: cavity fabrication, surface treatment and cavity cooldown to 4.2 K. The cavity resonant frequency evolves after each process and this needs to be characterized. By analytical calculation, electromagnetic simulation and RF measurements, the frequency shift can be well determined, while the frequency uncertainties can be estimated [4]. Possessing a good knowledge of the frequency variation, a pre-tuning step was determined and described in this paper. The length of the cavity outer conductor is used as a free parameter to recover the frequency shift.

THE TARGET FREQUENCY

The target frequency of the cavity is 166.6 MHz at 4.2 K with the cavity immersed in a 1 bar of Liquid Helium bath while having vacuum inside. According to simulations, 19 kHz from the cavity frequency will be lost by pumping the cavity volume from air to vacuum maintaining the ambient pressure of 1 bar. Figure 1 shows the step-by-step scaling of the cavity frequency. Warming up the cavity from 4.2 K to 293 K will thermally expand the cavity volume and thus bring down the cavity frequency by 220 kHz. The last contribution to the frequency shift is the permittivity of the ambient air. This will contribute -53 kHz to the cavity measured in air. Finally the cavity measured in ambient environment with 20°C, 50% relative humidity and normal pressure shall have a resonant frequency of 166.446 MHz in order to ensure a correct frequency at 4.2 K. This will serve as a guide during the following cavity process step. The exact number of the frequency shift will only be determined by measurements as described in the following sections.

f_0(MHz)	Δf	Temp.	Cav. inner volume	Cav. outer volume
166.600		4.2K	Vacuum	1bar LHe
	0 kHz	Tuning force→0kgf		
166.600		4.2K	Vacuum	1bar LHe
	+19 kHz	Pressure differ. between inside/outside (with supports)		
166.619		4.2K	Vacuum	Vacuum
	-220 kHz	4.2K→293K (with supports)		
166.399		293K	Vacuum	Vacuum
	-53 kHz	Vacuum → air		
166.346		293K	Ambient air	Ambient air
	+100 kHz	After BCP&Annealing → before BCP&Annealing (remove 200μm) (+39kHz, if uniformly remove 200μm)		
166.446		293K	Ambient air	Ambient air

Figure 1: The step-wise frequency scaling from simulation.

The cavity has been supported by 4 titanium rods and 2 backplanes as shown in Fig. 2 to ensure a proper mechanical rigidity during pumping to vacuum and cooldown to 4.2 K. The exploded view of the cavity is shown in Fig. 3 noted with components' name. The following study was based on the supported cavity with LBP flange fixed [5].

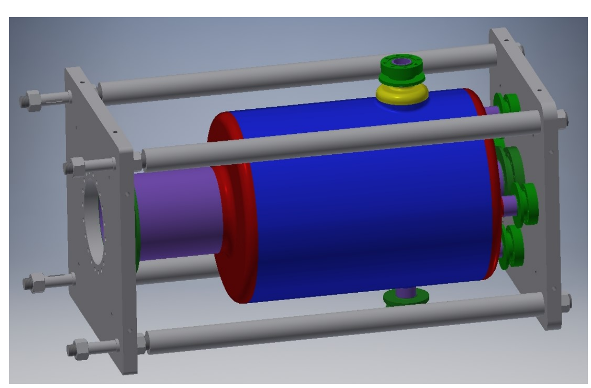

Figure 2: The cavity with supporting frame.

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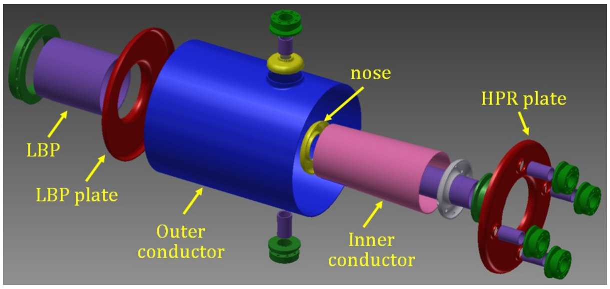

Figure 3: The naming of components.

THE FREQUENCY VARIATION

The resonant frequency of a PoP cavity can be varied by: manufacturing tolerances, surface treatment after fabrication, cooldown process, presence of dielectrics in the cavity volume and eventually Lorentz force detuning. The impact of these contributors to the cavity frequency are described in detail along with measurement validations in this section.

The Manufacturing Tolerances

The geometry of a PoP cavity is shown in Fig. 4 together with its main geometry parameters relevant to the cavity frequency. The frequency responses to the geometry changes are listed in Table 1. The 0.16° change of taper_angle corresponds to a 1 mm change in the vertical direction. The nose of the cavity inner conductor and the LBP plate can be modeled as a capacitor where the capacitance depends on the accelerating gap length. The frequency variation from the nominal value with respect to the gap length is shown in Fig. 8 as the black circles indicate. Δf is not the same for every gap length. The larger the gap, the less the capacitance will be changed by a same amount of gap variation, therefore the less sensitive the frequency will change. The gap length will be used as a free parameter to tune the cavity frequency after manufacturing.

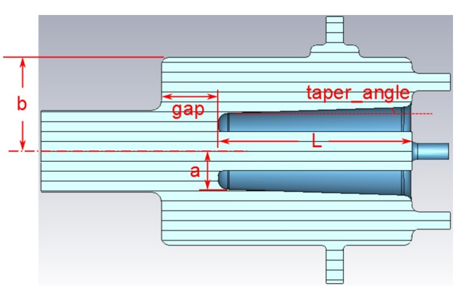

Figure 4: The main geometry parameters of the cavity.

Pump to Vacuum

The change of the cavity inner volume from normal air to vacuum at 4.2 K alters the relative electric permittivity ϵ_r, thus varies the cavity resonant frequency. In addition, the pressure difference between the cavity inside and outside volume will deform the cavity shape thus alter the frequency. These have been calculated by ANSYS simulation codes [6] and amount to +53 kHz for permittivity change and −19 kHz for shape deformation by pumping to vacuum.

Table 1: The Frequency Sensitivity to +1 mm Geometry Changes From the Nominal Value

Parameter	Δf (kHz)
a	−46
b	−152
L	−353
gap	+38
taper_angle	+546

The Cooldown Process

The cool down of the cavity from room temperature to 4.2 K will alter the resonant frequency due to thermal contraction of the cavity geometry. This has been calculated by using ANSYS simulation codes and is presented in detail in [5]. The frequency shift during cooldown was calculated to be +220 kHz.

The BCP and Annealing

The cavity treatment after fabrication consists 2 times 75' BCP, 750°C annealing and one time 30' BCP [7]. The cavity frequency was measured after each treatment step. It increased by 81 kHz after 2 times 75' BCP corresponding to ~110–160 µm removal, while the simulation indicated a +39 kHz increase if uniformly removing 200 µm. Further studies suggest a ~260 µm removal on the inner conductor nose as shown in Fig. 5 due to a direct facing to the chemicals thus higher removal rate during BCP. On the other hand, 750°C annealing brought down the frequency by 37 kHz. Finally cavity treatment steps moved the frequency up by 76 kHz in total.

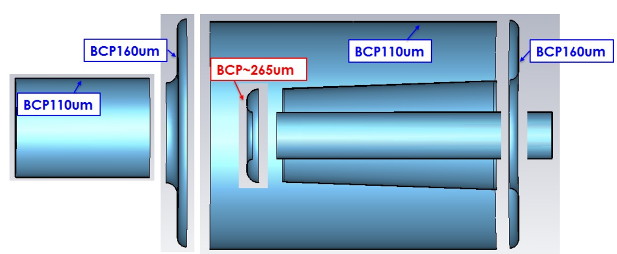

Figure 5: The surface removal after 75'+75' BCP.

Lorentz Force Detuning

The Lorentz force detuning of the cavity was simulated by ANSYS simulation codes and was then measured during cavity vertical test at cryogenic temperature. Figure 6 shows the frequency detuning by Lorentz force measured at various cavity gradient at 4.2 K and 2 K. At nominal gradient (E_{acc} = 14.5 MV/m), the cavity resonant frequency is detuned by -430 Hz at 4.2 K. This corresponds to a detuning coefficient of κ = -2.05 Hz/(MV/m)^2, which is very comparable to the simulation results [5].

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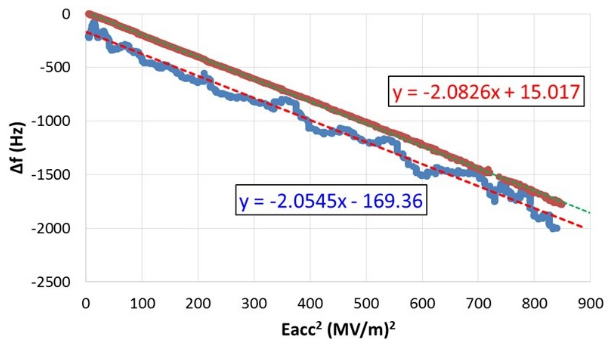

Figure 6: The measurements of Lorentz force detuning.

CAVITY FREQUENCY PRE-TUNING

The cavity was initially produced with longer-than-needed outer conductor. The aim of the pre-tuning is to tune the cavity frequency to a previously determined target frequency by trimming the cavity outer conductor before the final welding.

The measurement of the cavity resonant frequency at warm is conducted by measuring the scattering parameter S_{11} where the ambient temperature, humidity and barometric pressure are monitored. A typical measurement setup is shown in Fig. 7. The frequency is measured by using a simple copper pickup antenna and its perturbation to the cavity frequency was corrected. Before performing the frequency measurement it is important to assure that the cavity is and remains in thermal equilibrium with the environment. This is essential to avoid frequency measurement errors.

Figure 7: The frequency measurement setup.

As described in previous sections,“gap” is the free parameter for pre-tuning. Given a target frequency, the desired gap will be different from cavity to cavity due to mechanical tolerance and subsequent cavity treatment foreseen after fabrication. For a newly produced cavity, the desired gap can be determined by a one-time measurement of initial cavity frequency and initial gap value along with the previously determined reference curve and target frequency at warm. As shown in Fig. 8, the reference curve is the cavity frequency response to gap variations and has been previously determined by electromagnetic simulations. This is plotted as the black circles. The initial gap was measured to be 137.5 mm and the measured frequency was 167.803 MHz after 24 hours of thermalization in metrology lab and normalized to 20°C and 50% relative humidity with normal pressure. This is shown as the red solid dot. Moving down the calibration curve until it intersects the initial measured point, the blue solid curve is the working curve for the current cavity. This curve describes the cavity frequency response to different gap values for the current cavity. The ideal target frequency has been previously determined to be 166.658 MHz reserving some room for unexpected frequency loss. This is denoted as the black dashed line. The intersection of the working curve and the ideal target frequency line is the suggested ideal point and is denoted by the solid green hexagram. The trimming was however conducted in steps in order to validate the method and the measured points are shown as the hollow squares. The last one in red has a larger deviation from the working curve due to cavity plate deformation during welding. This can be well corrected by cavity pre-tuning before cool down.

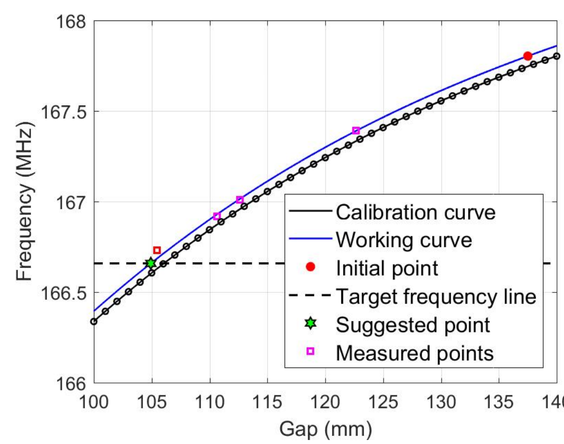

Figure 8: The tuning mechanism.

The frequency of the PoP cavity was carefully monitored during each process step and is shown in Fig. 9. The frequency at 4.2 K was measured to be 92 kHz higher than 166.6 MHz. This can be attributed to the unexpected larger frequency shift due to BCP and cooldown process compared to simulations. This however can be easily corrected by less than 1 mm of deformation of the LBP plate towards the inner conductor cone [5]. At this stage, we conclude that the pre-tuning of the PoP cavity was completed.

FINAL REMARKS

The contributions to the frequency variation for the 166.6 MHz PoP cavity have been analyzed in detail. A pre-tuning method has been proposed to accommodate the

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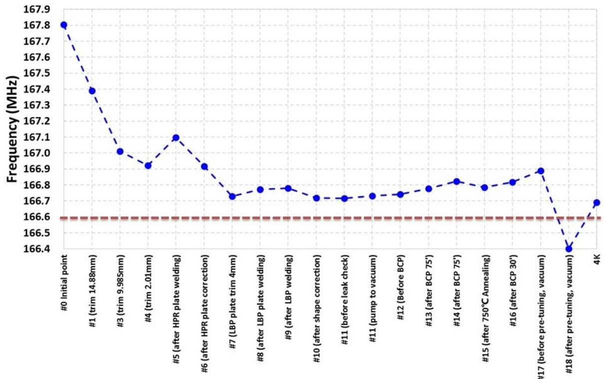

Figure 9: The frequency variation.

frequency shift by using the cavity length as a free parameter. The PoP cavity frequency has been carefully monitored during each process and it has been proved that the cavity frequency is under control. One needs to notice that the pre-tuning method only requires one-time measurement of the cavity frequency and the cavity length.

ACKNOWLEDGEMENTS

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