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MECHANICAL DESIGN AND HORIZONTAL TESTS OF A DRESSED 166.6 MHz QUARTER-WAVE $\beta = 1$ SRF CAVITY SYSTEM*

X.Y. Zhang†, P. Zhang, Z.Q. Li, Q.Y. Wang, H.Y. Lin, Q. Ma, Z.H. Mi, X.R. Hao, D.B. Li,
Institute of High Energy Physics (IHEP), Beijing, China

Abstract

A 166.6 MHz quarter-wave $\beta = 1$ superconducting proof-of-principle cavity has been designed and recently been dressed with a helium jacket, fundamental power coupler and tuner. The cavity was subsequently installed in a modified cryomodule and tested in a horizontal manner at both $4.2K$ and $2K$. The helium jacket was successfully developed with a focus on minimizing frequency shift due to helium pressure fluctuation while retaining a reasonable tuning range. The Lorentz force detuning (LFD) and microphonics were also optimized during the design. The df/dp and LFD coefficient were measured to be −3.1 Hz/mbar and −0.76 Hz/(MV/m)^2. These are in good agreement with simulations. Future work is mainly to reduce the stiffness of the cavity and further suppress the vibration mode of the inner conductor.

INTRODUCTION

The High Energy Photon Source (HEPS) is 6 GeV, $1.3km$ storage ring light source with ultralow-emittance to be built in the northeast suburb of Beijing [1]. As the R&D project for HEPS, the HEPS test facility (HEPS-TF) has started in 2016 to develop key technologies including the 166.6 MHz superconducting cavity for the storage ring. A proof-of-principle 166.6MHz quarter-wave β=1 cavity has been designed, fabricated, post-processed and vertical tested in 2017 [2,3]. In this paper, we will report on the helium vessel design and the horizontal test results obtained at IHEP in a modified cryomodule. At the same time, the analysis of the simulation and measurement results will also be given, which will provide an important reference for the design of the real cavity in the future.

DESIGN OF THE DRESSED CAVITY

After the vertical test of the superconducting cavity was successful, the liquid helium (LHe) vessel used for the horizontal test was designed and optimized. Sufficient stiffness, stability and tuning ability are the indicators that need to be considered in the mechanical design of the LHe vessel. However, too much stiffness may result in reduced tuning capability. This will be the biggest challenge of the mechanical design. The model of the LHe vessel is built by SolidWorks CAD [4], and the mechanical simulation is implemented by ANSYS codes [5]. The structure diagram of the LHe vessel is shown in Fig. 1. The biggest advantage of the LHe vessel is that there is no bellows, and the pressure sensitivity can be close to the ideal value of 0 Hz/mbar. The main parameters of the design include the LBP blend of the cavity (R), the wall thickness of the LHe vessel end plate (Tep), the wall thickness of the LHe vessel cylinder (Tcy), and the blend of the LHe vessel end cover (a, b).

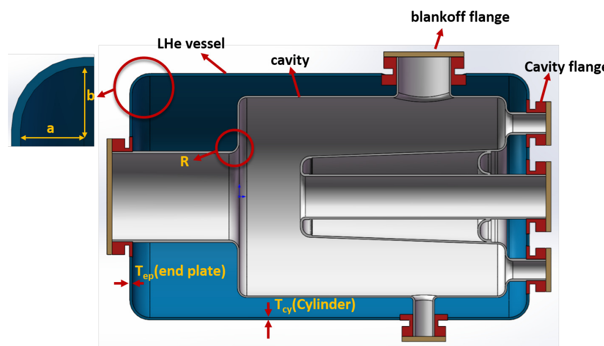

Figure 1: The cross section of the dressed cavity.

The optimization results show that the larger R helps to reduce the pressure sensitivity, and has little effect on the tuning range and Lorentz coefficient. The optimization curves are shown in the Fig. 2. Since the increased R will cause Epeak to rise, R is chosen to be 20 mm.

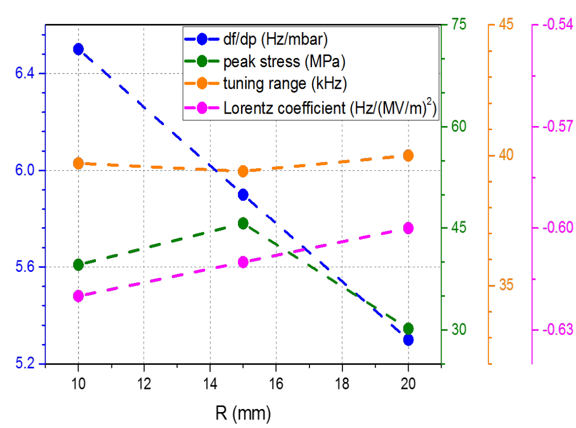

Figure 2: The optimization results of R.

Since the df/dp is a positive value, it can be continuously reduced and approached to the ideal 0 Hz/mbar by increasing the blend of the LHe vessel end cover (a, b). The simulation results are shown in the Fig. 3. The optimized pressure sensitivity was reduced to 0.69 Hz/mbar, the tuning range was slightly decreased, and the peak stress and the Lorentz coefficient are almost unchanged.

In order to decrease the weight of the LHe vessel, the wall thickness Tcy is reduced from 5 mm to 4 mm. Simulation

* Work supported by HEPS-TF project.
† zhangxinying@ihep.ac.cn

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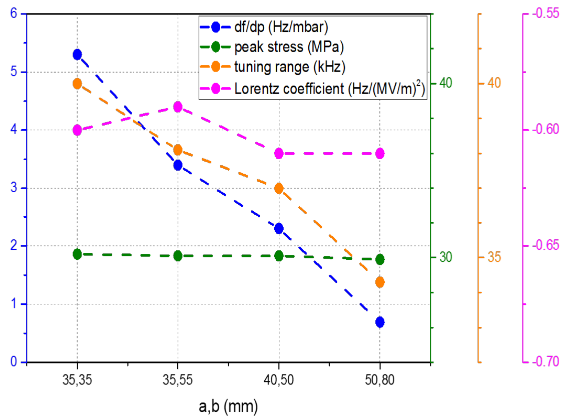

Figure 3: The optimization results of a and b.

results show that the impact on mechanical properties is small. Increasing the wall thickness Tep of the LHe vessel end plate can greatly reduce the pressure sensitivity, improve the rigidity, and have little influence on the peak stress, the tuning range and the Lorentz coefficient. The optimization curves are shown in the Fig. 4. Finally Tep was chosen to be 20 mm.

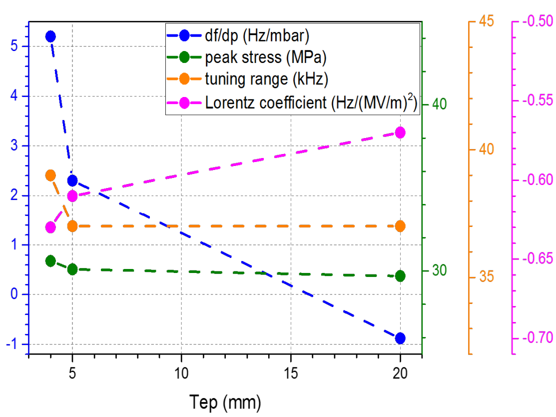

Figure 4: The optimization results of Tep.

The mechanical properties after optimization of the LHe vessel are summarized in Table 1. After adding the LHe vessel, the pressure sensitivity is greatly reduced and close to 0 Hz/mbar, the Lorentz coefficient and the peak stress are improved, but the tuning ability is lowered.

Table 1: The Mechanical Properties of Dressed Cavity

Parameter	Unit	Cavity	Dressed cavity
df/dp	Hz/mbar	359.4	-0.88
peak stress	MPa	46.9	29.7
Lorentz coefficient	Hz/(MV/m)^2	-5.2	-0.57
tuning rang	kHz	100	37

FABRICATION

3D view of the dressed PoP cavity is shown in Fig. 5. The end plate of the LHe vessel is selected as a square titanium plate, which provides great convenience for processing and installation positioning. The inlet port of liquid helium is located below of the vessel, and the chimney is located above, opposite to each other. The angle of inclination of the coupler with the vertical direction is 20°, in order to match the interface of the cryomodule and minimize the contamination of the cavity during coupler installation.

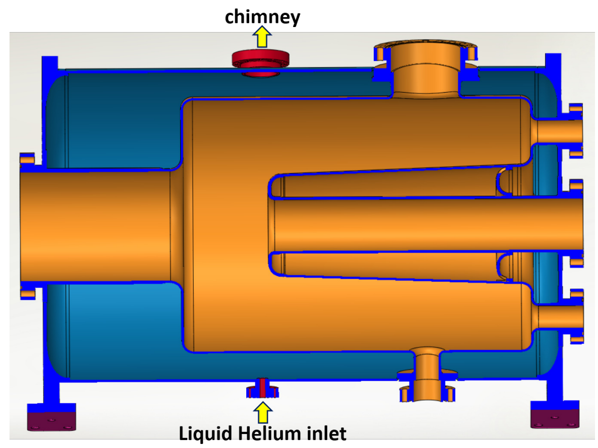

Figure 5: 3D schematic of the dressed PoP cavity.

The material of the LHe vessl is titanium. The ratio of thermal contraction of Titanium (0.134 %) is almost same as Niobium (0.129 %). Therefore, the cavity will not be applied with too much mechanical stress from the LHe during the cool down and warm up process. In addition, titanium is a non-ferromagnetic metal that does not affect the test performance of the superconducting cavity. Titanium also has high strength, so the flange material of the inlet and outlet of helium is titanium. Magnetic shield is between the LHe vessel and the PoP cavity and is made of permalloy to shield the magnetic field around the cavity. The LHe vessel is machined and welded to the vertically test cavity. The fabricated LHe vessel with cavity is shown in Fig. 6.

HORIZONTAL TEST

The dressed cavity has been post-processed, assembled with the coupler and tuner into a superconducting cavity component, and then integrated with the modified cryomodule. The pictures of the cavity in modified cryomodule is shown in Fig. 7.

For horizontal test, the quality factor (Q_0) versus transverse voltage (V_c) was measured at 4 K and 2 K. The results were shown in Fig. 8. The cavity Q_0 at designed transverse voltage (when V_c=1.2 MV) was tested to be 7.6×10^8 at 4 K and 8.4×10^8 at 2 K, exceed the designed goal (5×10^8 at 4 K). The maximum transverse voltage of HT reached 1.6 MV, and its increase was limited by cavity quench. After preliminary analysis, the quench was caused by insufficient

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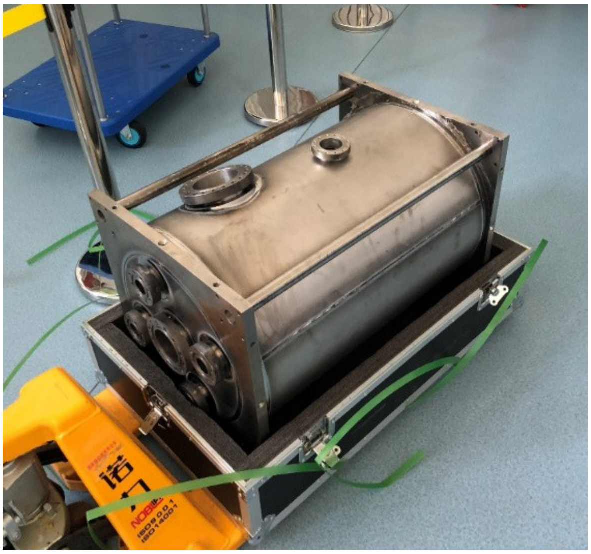

Figure 6: The fabricated LHe vessel with cavity.

Figure 7: The photos of the dressed cavity installed in the modified cryomodule.

height of the coupler port on the cavity, which would cause the temperature of the Nb/45Ti flange to rise rapidly. During the HT, the maximum radiation dose was about 2.7 mSv/h. The test results demonstrate the performance of the dressed cavity meets the design specifications of the HEPS.

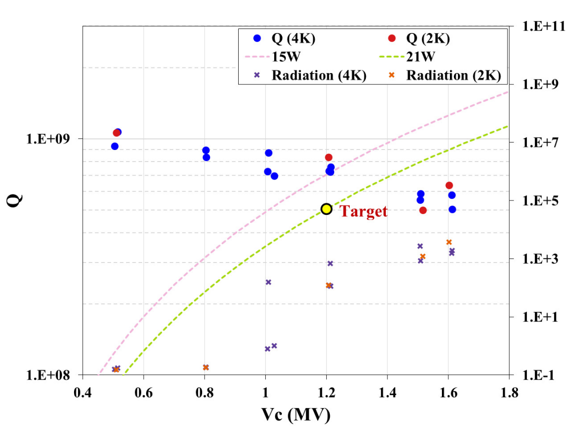

Figure 8: The HT results of the dressed cavity.

Frequency Control During Cool Down

When the cryomodule is cool down, the thermal gradient ΔT of the cavity spatial temperature should be <50 K to avoid mechanical stress caused by thermal contraction. During the twice cool down processes, the temperature rise of the cavity is almost the same, 249 kHz and 247 kHz, as shown in Fig. 9. The result shows that superconducting acceleration component composed of the PoP cavity, couplers, tuner, etc., have a good consistency in the installation and integration of the cryomodule.

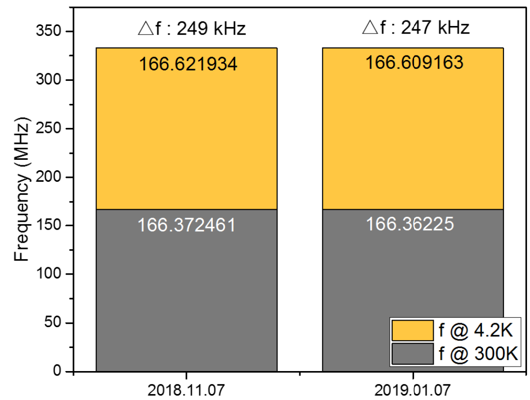

Figure 9: Frequency shift comparison of the cavity at cool down process.

LFD

The change in cavity resonant frequency due to Lorentz force detuning was shown in Fig. 10. The Lorentz coefficient at 4.2 K horizontal test was measured to be K_L=-0.76 Hz/(MV/m)^2, consistent with the simulation result K_L=-0.57 Hz/(MV/m)^2. The maximum Lorentz force detuning under operating voltage 1.2 MV is 76 Hz, which is much smaller than -3dB bandwidth of the cavity, and has little effect on the stability of the cavity field.

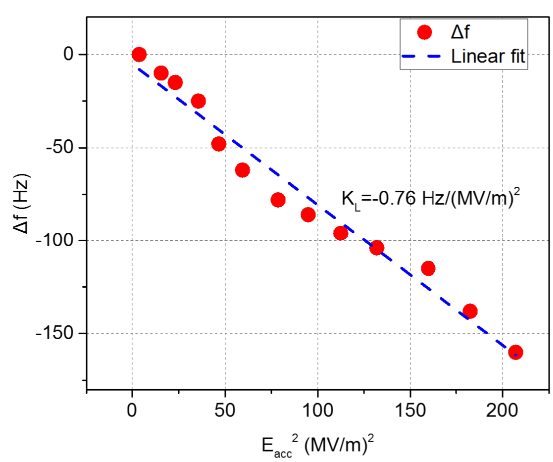

Figure 10: Lorentz force detuning at 4.2 K horizontal test.

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Pressure Sensitivity

The pressure sensitivities measured by cool down and warm up were -3.1 Hz/mbar and -3.7 Hz/mbar, which is approximately four times the simulation result (-0.88 Hz/mbar). The results were summarized in Table 2. The error may come from the constraint that the connection between the support base of LHe vessel and the cryomodule is weaker than the fully fixed boundary for the support during simulation. In addition, the changes of LHe pressure during cool down and warm up are basically the same, but the frequency shift of the cavity warm up is about 590 Hz more than cool down. This phenomenon was observed in both horizontal test, and may be caused by the different working states of the tuner. For ±3 mbar LHe pressure fluctuations, the maximum frequency shift is only ±11 Hz, which is much lower than the frequency detuning when the LHe vessel is not applied. The test results show that the pressure stability of the LHe vessel is very good.

Table 2: The Pressure Sensitivity of the Cavity at HT

Simulation (Hz/mbar)	Test result (Hz/mbar)	Remark
-0.88	-3.1	cool down (2K→4K)
	-3.7	warm up (4K→2K)

Tuning

During the horizontal test, the tuner worked smoothly and successfully adjusted the resonant frequency of the cavity to 166.6 MHz. Fig. 11 is the module of tuner. According to the pressure sensor and frequency test results, the stiffness of the cavity was calculated to be 10.7 kN/mm. This stiffness is a bit large and needs further improvement in the future.

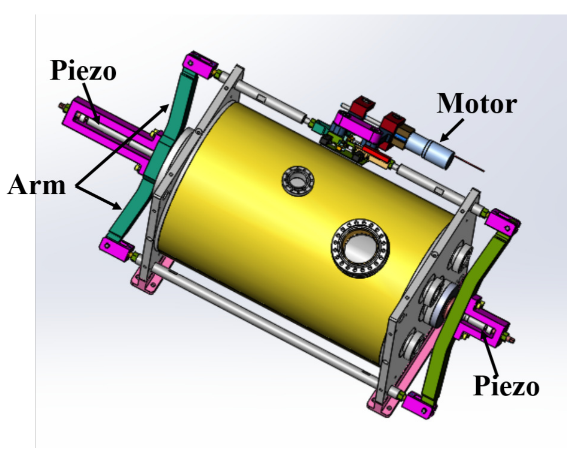

Figure 11: The schematic of tuner.

Microphonics

The spectrum of the microphones was observed in two horizontal tests, as shown in Fig. 12. Since the simulation of microphone is greatly affected by the model mass distribution and boundary conditions, the error of the two measurement spectra may come from the pipeline modification in the cryomodule before the second horizontal test. The higher the relative amplitude of the curve in the figure, the stronger the coupling of the cavity to the external source at the corresponding frequency.

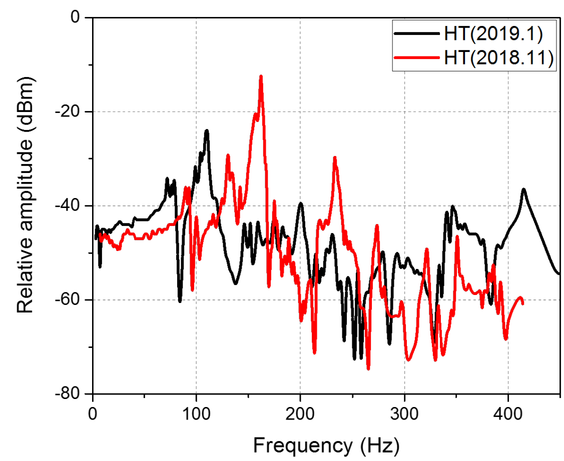

Figure 12: Microphone spectrum measured at horizontal tests.

In both tests, the most coupled mode was the inner conductor swing mode. Fig. 13 shows the measurement results in November 2018. The relative amplitude of the vibration mode at 158 Hz is about -10.42 dB, and the vibration frequency is very close to the simulated 164.85 Hz. How to suppress the vibration mode of the single-swing motion of the inner conductor is the direction of our future research. Since the QWR cavity is placed horizontally during operation, the suppression method for this mode requires further study.

CONCLUSION

The helium vessel of the 166.6 MHz quarter-wave $\beta = 1$ PoP cavity was successfully designed and manufactured. Low pressure sensitivity of -0.88 Hz/mbar was achieved. The cavity was later assembled with power coupler and tuner and finally installed in a modified cryomodule to complete the horizontal test at 4K and 2K. The test results show that the cavity meets the design requirements for HEPS. The mechanical properties of the cavity were also measured in the horizontal test and the results agreed well with simulations. These serve as a good reference for the real cavity development. Future work is to improve the tuning performance and to suppress the vibration mode of the inner conductor.

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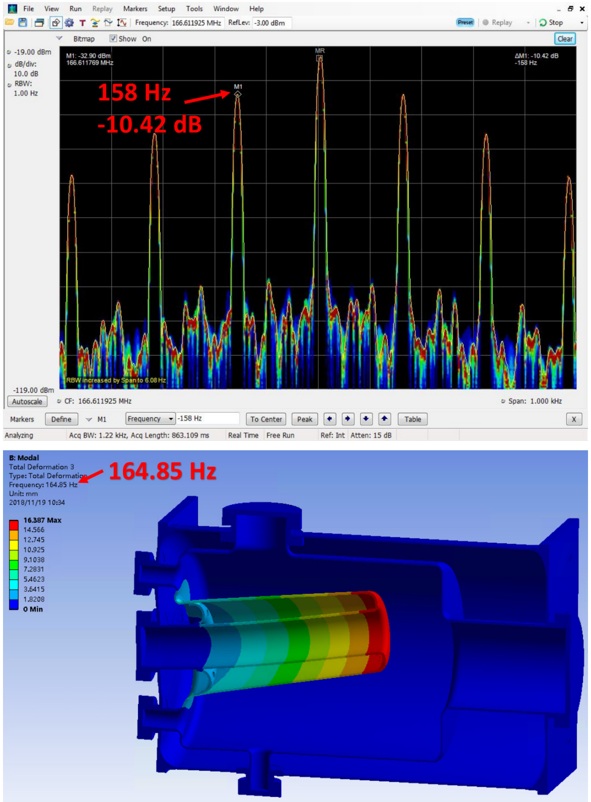

Figure 13: Comparison of simulation (down) and tested (up) vibration mode.

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