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A 166.6 MHZ PROOF-OF-PRINCIPLE SRF CAVITY FOR HEPS-TF: MECHANICAL DESIGN AND FABRICATION

X. Zhang*, Z. Li, P. Zhang, H. Lin, Y. Sun, Institute of High Energy Physics (IHEP), Beijing, China
X. R. Hao[1], Institute of High Energy Physics, Beijing, China
[1]University of Chinese Academy of Sciences, Beijing, China

Abstract

166.6 MHz superconducting RF cavities operating at 4.2 K have been proposed by IHEP for the High Energy Photon Source - Test Facility (HEPS-TF). The cavity is a quarter wave resonator with beam going through the cavity inner conductor. The cavity and its stiffness were designed and optimized to meet pressure safety requirement and to reduce frequency sensitivity due to helium pressure fluctuations. Tuning sensitivity, Lorentz force detuning and microphonics were also simulated. Most calculations have been validated by experiments. This paper reports the mechanical design and fabrication details of the first proof-of-principle cavity.

INTRODUCTION

The High Energy Photon Source (HEPS), a 6 GeV kilometre-scale, ultralow-emittance storage ring light source, is to be built in the suburb of Beijing, China [1]. As the R&D project for HEPS, a test facility namely HEPS-TF has been approved to prototype key technologies and components. The new injection scheme [2] requires two RF frequencies for the storage ring, meanwhile limited by the development of the fast kicker system, 166.6 MHz has been chosen as the main RF frequency and the 499.8 MHz for the third harmonic cavity respectively. The main parameters of the double-frequency RF system [3] are listed in Table 1. Extensive efforts have been made on the 166.6 MHz superconducting (SC) cavity and relevant studies of the RF system.

Table 1: Main Parameters of the RF System

Parameter	Fundamental cavity	Harmonic cavity
Frequency	166.6 MHz	499.8 MHz
RF voltage	3.5 MV	3.2 MV
Number of cavities	4	2
RF voltage / cavity	1.2 MV	1.7 MV
Peak power / cavity	150 kW	200 kW

Due to the low operating frequency (166.6 MHz) and $\beta = 1$, a quarter wave shape was adopted, which makes the cavity geometry suitable for manufacturing. A proof-of-principle (PoP) cavity has been designed and optimized [4]. The RF model is shown in Fig. 1.

This paper describes the mechanical design with a focus on the pressure sensitivity, cavity rigidity, Lorentz force detuning (LFD), stress analysis and microphonics. The fabrication details of the PoP cavity will also be mentioned.

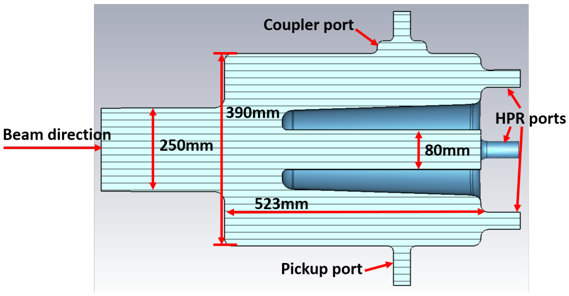

Figure 1: The 166.6MHz PoP cavity.

THE MECHANICAL DESIGN

The mechanical design of the 166.6 MHz PoP cavity was optimized using SolidWorks CAD [5] and ANSYS simulation codes [6]. The measurement results show good agreement with the calculations.

Model

The mechanical model for study is shown in Fig. 2. To simplify the simulation, some features of the model are removed, such as the coupler and pickup ports. The wall thickness of some cavity parts is increased to reinforce its strength. Since the beam tube in the inner conductor is too long, a stiffening ring was added. Two stiffeners were designed, and the bowl shaped one was finally chosen due to better performance.

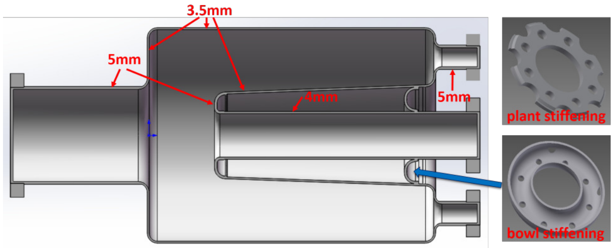

Figure 2: The mechanical model.

The cavity is made of RRR300 niobium and Ti-45Nb alloy. The maximum allowable stress (S) is determined by [7]

$$S = \min\left(\frac{\text{Ultimate strength}}{3.5}, \text{Yield strength} \times \frac{2}{3}\right). \qquad (1)$$

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* zhangxinying@ihep.ac.cn

Thus the S of Nb is 47 MPa at room temperature, and 212 MPa at 4 K. The S of Ti-45Nb is 156 MPa at room temperature and 4K.

Pressure Sensitivity

The PoP cavity works at 4.2 K in the liquid helium (LHe) bath. Two boundary conditions at beam ports (a fully fixed condition and a completely free condition) were calculated. The results are summarized in Table 2. The real boundary condition is somewhere between the fixed and the free case, thus df/dp is between +2.7 Hz/mbar and −359.4 Hz/mbar. Our previous experience indicates a helium pressure fluctuation of approximately 2 mbar [8]. This results in a frequency variation of 5.4 Hz ~ 719 Hz. This range of frequency shift is too large, and the design of LHe vessel should be considered to reduce it. For vertical test (VT), a support structure can be added to fasten the beam tube.

Table 2: The Pressure Sensitivity Results

Boundary condition	**df/dp**
fully fixed	+2.7Hz/mbar
completely free	−359.4Hz/mbar

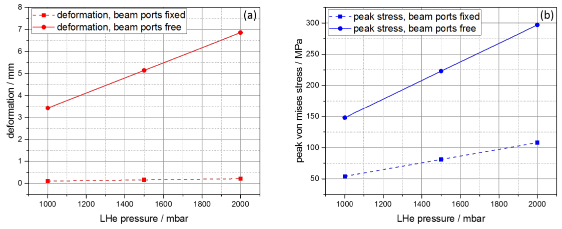

Figure 3: The peak deformation and stress of the cavity under different pressures.

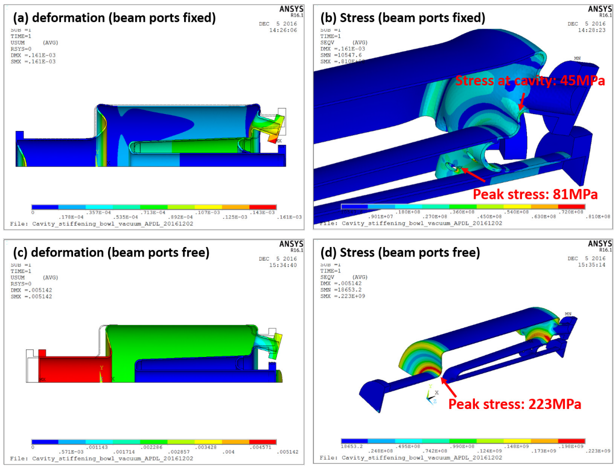

Figure 4: The peak deformation and stress of the cavity under 1.5 bar of pressure.

The peak deformations and the peak von mises stress of the cavity are shown in Fig. 3. The results vary linearly with the pressure changes. We consider the maximum pressure of the liquid helium of 1.5 bar. The peak stress is located at the left beam port when beam ports are free and at the stiffening ring when beam ports are fixed. The value is 223 MPa and 45 MPa respectively. The peak deformation and stress of the cavity under 1.5 bar of pressure are shown in Fig. 4. The stress with beam ports free exceeds the allowable limit, and LHe vessel or a support structure is needed to reinforce it.

A support structure of the cavity was designed to reduce the df/dp and maximum stress. The simulation results of the df/dp is −19.4 Hz/mbar, and the frequency drift is 38.8 Hz. We can see that performance of pressure sensitivity has been drastically reduced. Meanwhile, the peak von Mises stress is less than 47 MPa, which meets the safety requirements. The support structure with stress results are shown in Fig. 5. The measured df/dp is -28.98 Hz/mbar, shown in Fig. 6. The measured result is close to calculation, and the differences might be attributed to different boundary conditions.

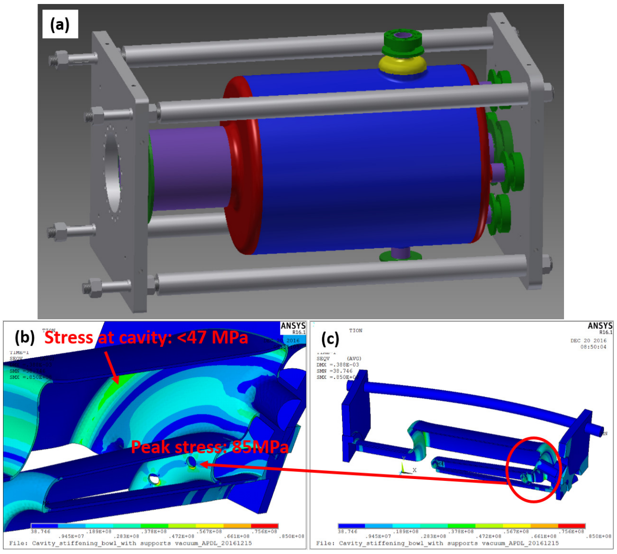

Figure 5: The support set (a) and the peak stress(b, c) of the cavity for VT.

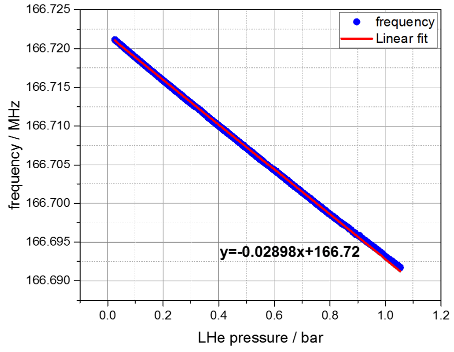

Figure 6: The measured df/dp from VT.

Tuning

The tuning force is applied on the left port and the resulting deformation and stress are summarized in Fig. 7. The peak deformation and peak stress vary linearly with the tuning force. The tuning rang R and the tuning force F are related to the stiffness k and the tuning sensitivity s by

$$R = \frac{s}{k} \times F. \tag{2}$$

Calculated s is 101.5 kHz/mm, and k is 1857 N/mm. The measurement results of s is 105.5 kHz/mm, which shows good agreement with the calculations. The measured s is shown in Fig. 8. The peak deformation and peak von Mises stress under 2 kN are shown in Fig. 9. This will give a coarse tuning range of 100 kHz. In the future design of LHe vessel, the challenge lies in the maintainence of a good tuning range while suppressing helium pressure sensitivity and peak stress.

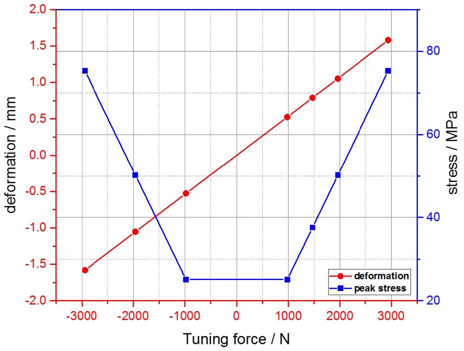

Figure 7: The deformation and stress under tuning force.

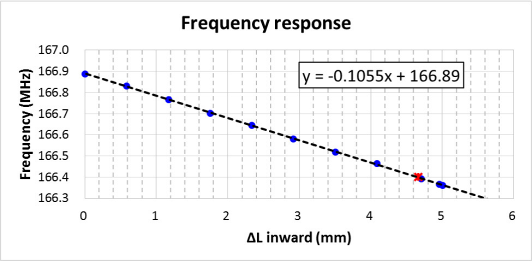

Figure 8: The measured s from pre-tuning.

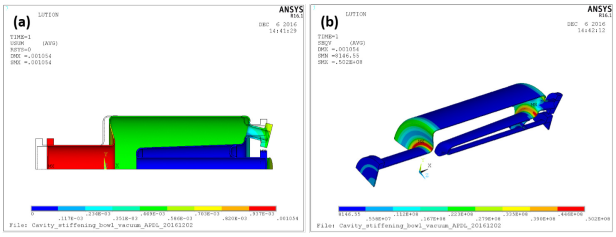

Figure 9: The peak deformation and stress under 2 kN.

Lorentz Force Detuning

During operation, magnetic field (H) and electric field (E) will produce radiation pressure in the RF cavity wall. The total Lorentz pressure can be calculated by

$$P = \frac{1}{4}(\mu_0 H^2 - \epsilon_0 E^2), \tag{3}$$

where μ_0 is the permeability of vacuum and ϵ_0 is the permittivity of vacuum.

The Lorentz force detuning (LFD) is studied in two boundary conditions (free and fixed beam ports). The calculation and measurement results of the frequency shift w.r.t. the accelerating gradient are shown in Fig. 10. The LFD coefficient is -2 Hz/(MV/m)^2 with ports fixed and -5.2 Hz/(MV/m)^2 with ports free. The total frequency shift due to Lorentz force is between -288 Hz and -748.8 Hz at Vc=1.5 MV. The maximum deformation is located at the high electric field region as shown in Fig 11. For VT, a support structure shown in Fig.5 (a) provides a good fixation to the beam ports, and the LFD coefficient measured to be -2.1 Hz/(MV/m)^2.

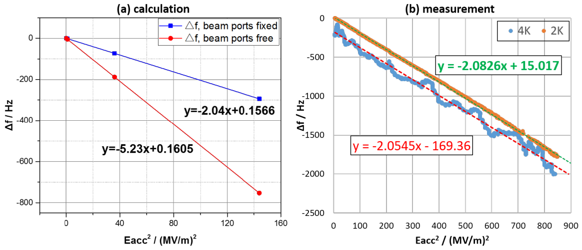

Figure 10: The LFD coefficient from calculation and VT.

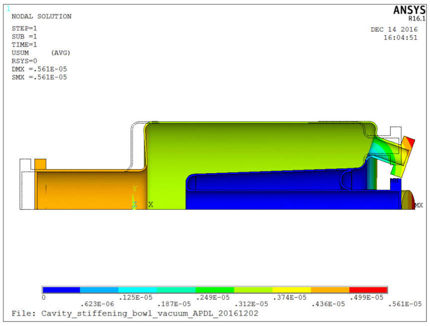

Figure 11: The peak deformation due to Lorentz force at Vc=1.5 MV.

Microphonics

The microphonics study was conducted with both beam ports fixed. The results are listed in Table 3, and the corresponding deformations are shown in Fig. 12. Low frequency modes around 100 Hz and below can lead to microphonic resonances which must be avoided. The frequency of the first 6 modes are all above 100 Hz. The LHe vessel can provide the HPR ports a good support, thus a better microphonics condition can be expected.

Table 3: The Results of the Microphonics Study

Mode	Frequency [Hz]	Vibration type
1	112.55	The outer conductor swings back and forth along Y axis
2	146.67	The inner conductor swings back and forth along Z axis
3	146.76	The inner conductor swings back and forth along X axis
4	232.8	The outer conductor rotates around Y axis
5	262.15	The outer conductor swings back and forth along X axis
6	271.36	The outer conductor swings back and forth along Z axis

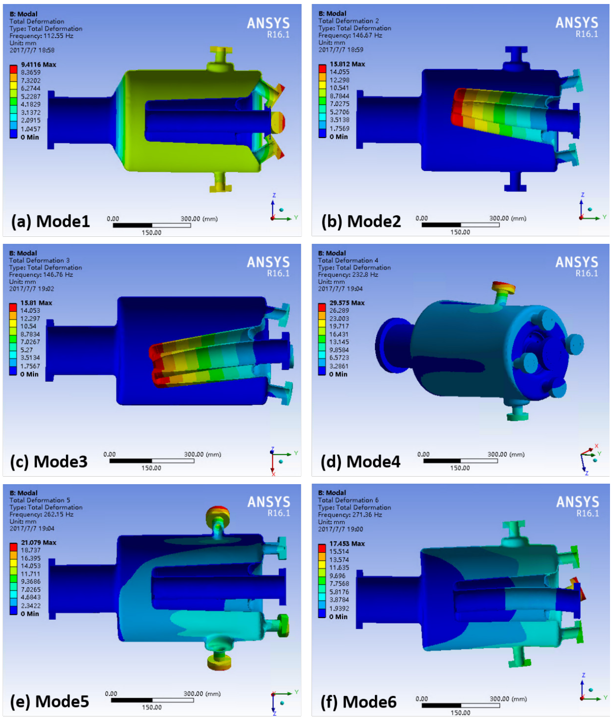

Figure 12: The first 6 mechanical modes.

THE CAVITY FABRICATION

The PoP cavity was fabricated in a domestic company, Beijing HE-Racing Technology Co. Ltd. It has 23 separated components, and the exploded view is shown in Fig. 13. Deep drawing, rolling and machining are the main manufacturing techniques. The material were checked carefully, and the tolerance of the cavity dimension are also supervised. Part of the finished components and inspection pictures are shown in Fig. 14.

The electron beam welding (EBW) was used to join all components together. In the process of technology design, all welding seams are located in the areas that can be polished, which greatly reduces the risk of cavity quality degradation. Some of the welded components are shown in Fig. 15. The length of the cavity outer conductor was chosen as a free parameter for the pre-tuning to accommodate the cavity frequency shift mainly due to mechanical tolerances during cavity production [9]. Before the final EBW, the inner surface of the cavity was carefully examined, and all defects were observed and grinded. The PoP cavity has been manufactured in January 2017. The frequency measurement and fabricated PoP cavity are shown in Fig. 16.

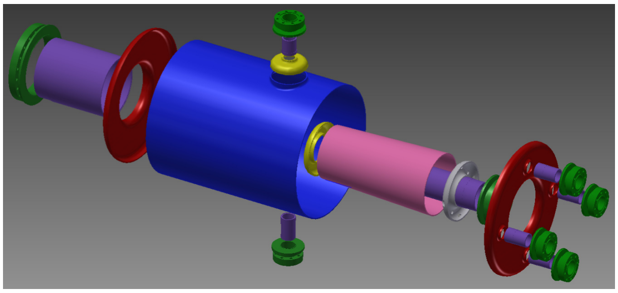

Figure 13: The exploded view of the PoP cavity.

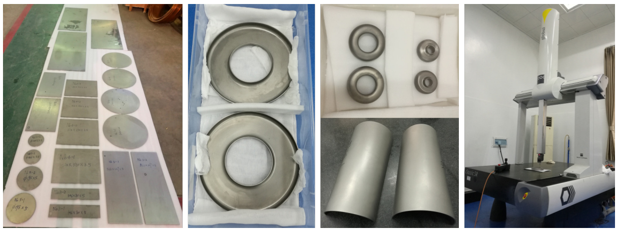

Figure 14: Part of the finished components and inspection pictures.

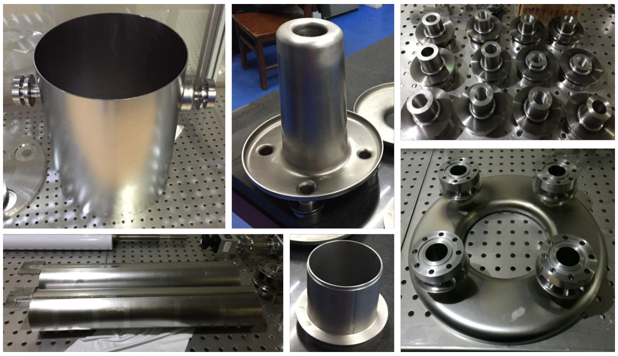

Figure 15: Some wleded components of PoP cavity.

CONCLUSION

A proof-of-principle 166.6 MHz SRF cavity has been proposed for HEPS-TF project. The mechanical design was studied and validated by experiments. A support structure has been designed to reduce the pressure sensitivity and Lorentz force detuning, and makes the peak von Mises stress to meet the safety requirements. The frequency of the first 6 resonate modes are all above 100 Hz. In the next step, LHe vessel will be designed. The challenge lies in the maintainence a good tuning range while suppressing helium pressure sen-

(a) frequency measurement (b) fabricated cavity

Figure 16: The frequency measurement and fabricated cavity.

sitivity, LFD coefficient and peak stress. The subsequence cavity treatment after fabrication has been conducted and the cryogenic vertical tests were recently made. The results largely exceed the design goal [4].

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