Study on the frequency tuning of the half-wave resonator at IMP [*]

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Abstract: The RF and mechanical coupled analyses are essential in superconducting cavity design in order to predict the deformation of the cavity walls and the frequency shift caused by the deformation. In this paper, the detuning caused by both bath helium pressure and Lorentz force is analysed and a tuning system has been investigated and designed to compensate the detuning by deforming the half-wave resonator along the beam axis. The simulations performed with ANSYS code show that the tuning system can adjust and compensate the frequency drift due to external vibrations and helium pressure fluctuation during operation.

Key words: HWR, vibration, tuning, ANSYS

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1 Introduction

A high current superconducting proton linac has been designed for the China Accelerator Driven Sub-critical System (CADS), undertaken by the Chinese Academy of Sciences since 2011, and two different injectors are being fabricated by the Institute of High Energy Physics (IHEP) and the Institute of Modern Physics (IMP) [1]. The Injector II of CADS is being designed and built by IMP. As shown in Fig. 1, Injector II consists of the ECR ion source, the low energy beam transport line (LEBT), the radio frequency quadruple (RFQ), the medium energy beam transport line (MEBT), and the superconducting accelerating section. For the superconducting accelerating section, 16 superconducting coaxial half-wave resonator (HWR) cavities are elaborately designed and arranged to accelerate the proton beam from 2.1 MeV to 10 MeV.

Superconducting (SC) coaxial HWR was first pro-

posed and prototyped in the early 1990s [2]. Recently, superconducting HWR structures are widely adopted in several proposed or proved high-intensity light ion linac projects [3–5]. Compared with the widely used SC quarter-wave resonator (QWR) [6], which has a more compact structure, one of the main advantages of HWR cavity is the geometry symmetry is in a vertical direction so that there is no vertical beam steering effect and is suitable for accelerating high intensity light ion beam. For spoke-type resonators, the HWR cavity is easier in fabrication and more stable, so that it can obtain a higher real-estate gradient, which makes it a possible alternative choice for filling the gap between RFQ and superconducting elliptical cavities [7]. However, because the load quality factor of SC cavity is usually extremely higher than that of normal conducting cavity, SC HWR cavities are highly sensitive to mechanical deformations due to the narrow bandwidth.
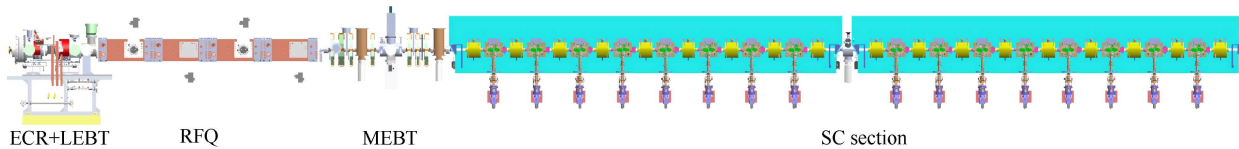
The designed RF parameters of the HWR cavity [8]

Fig. 1.   (color online) The schematic layout of Injector II for CADS.

for Injector II are shown in Table 1. Due to the narrow bandwidth, a frequency tuning system is proposed. In Section 3 of this paper discusses the general considerations on the design of this tuning system, including helium pressure influence and Lorentz force detuning effect, based on the calculating results with the ANSYS Code [9]. The detuning range and the upper limitation on accelerating gradient of this cavity are obtained. In the Section 4, the mechanical design based on the results of Section 3 is presented. The conclusions and suggestions for future research are given in the last section.

Table 1.   The main RF parameters of the HWR cavity.

parameter	value
frequency/MHz	162.5
β(optimization)	0.1
U_{acc}/MV(B_{peak}=50 mT)	0.78
$B_{peak}/E_{acc}{}^{1)}$/(mT/MV/m)	10.92
E_{peak}/E_{acc}	5.34
$R/Q_0/\Omega$	148
$G=R_s \cdot Q_0/\Omega$	28.5
$Q_0(K=4.4)$	1.4E9

1) The effective distance is the length between iris ($2\beta\lambda/3$).

2   Basic model setup

The structure of the superconducting HWR cavity with frequency of 162.5 MHz that will be discussed is shown in Fig. 2. Four rinsing ports are designed to guarantee the BCP processing and easy access to the inner conductor surfaces during the high pressure rinsing (HPR).
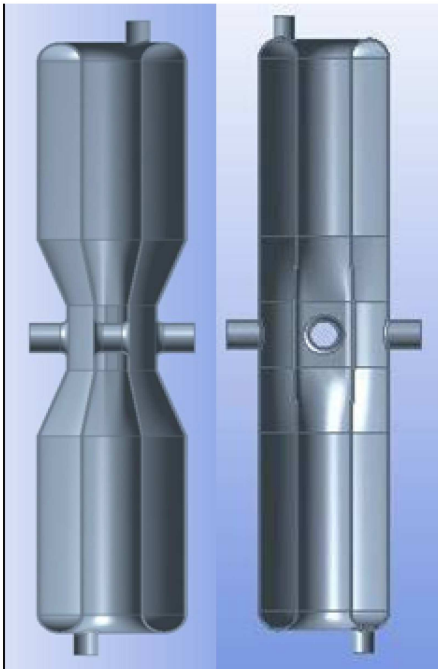

Fig. 2.   (color online) The structure of the HWR cavity.

The properties of niobium used in the coupled analysis in the following are listed in Table 2. It is worth pointing out that the thickness of niobium for the HWR cavity has changed to 2.8 mm because the BCP technique etches about 200 μm of the cavity surface.

Table 2.   The properties of niobium for SC HWR.

parameter	value
density/(g/cm^3)	8.6
tensile strength /MPa	400
Poisson's ratio	0.38
Young's modulus/GPa	105
thickness/mm	2.8

The thickness of the cavity wall has an influence on the level of frequency detuning. Due to the asymmetry of HWR cavity, all of the simulations and analyses are based on the results of the whole cavity calculation.

3   General considerations on the tuning system design

During the mechanical analysis, the variation of the eigenmode frequency was calculated. The relationship between changes in RF frequency and mechanical deformations is given by the Slater Perturbation Theorem [10].

$$\frac{\Delta f}{f_0} = \frac{\int_{\Delta v}(\mu_0\left|\bar{H}_0(\bar{x})\right|^2 - \varepsilon_0\left|\bar{E}_0(\bar{x})\right|^2)\mathrm{d}^3 x}{4 \cdot U_0}. \qquad (1)$$

From Eq. (1) we can see that the deformation in the electric field region and the deformation in the magnetic field region will give an opposite contribution to the frequency shift.

The dominant source of mechanical deformations comes from the vibrations that are due to various external sources. Generally, sources of frequency detuning for SC cavity include: (i) tolerances in the cavity parts; (ii) variation in welding shrinkage; (iii) variation in the frequency due to the attachment of the helium vessel; (iv) variation in the frequency produced by etching; (v) variation in the frequency during the cooling down; (vi) variation in the frequency shift by beam loading; (vii) variation in the liquid helium bath pressure; and, (viii) Lorentz force detuning. All these detuning effects should be taken into account during the frequency tuning before the horizontal test. Since most of these sources can be avoided by better machining and fabrication, in this paper we will mainly discuss the liquid helium pressure sensitivity and Lorentz force detuning effect.

3.1   Pressure sensitivity

One source of vibrations, operating at 4.2 K, are the fluctuations in the local helium bath pressure that arise
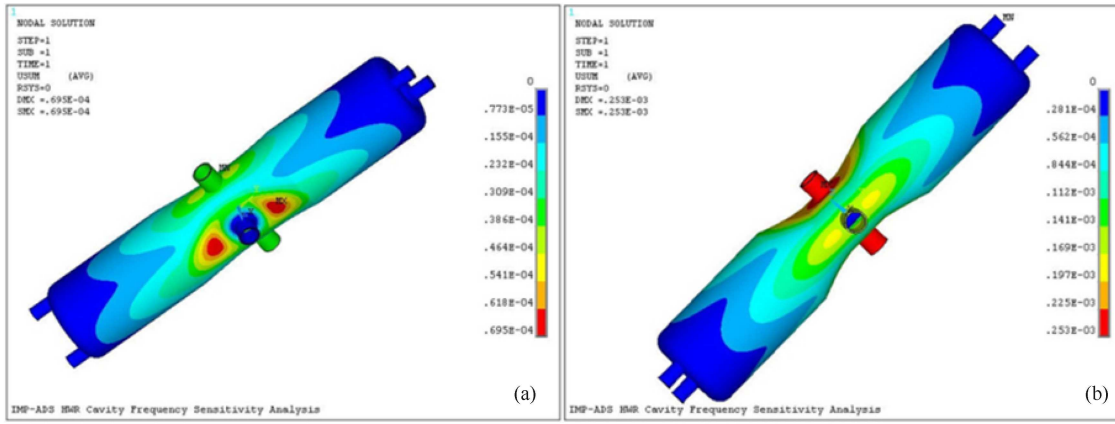
Fig. 3.   (color online) The deformation results of HWR with beam pipes fixed (a) and beam pipes free (b).

Table 3.   The simulation results for HWR cavity under one atmosphere load.

boundary	displacement/mm	stress/ksi	Δf/kHz	$\mathrm{d}f/\mathrm{d}P$/(Hz/mbar)
fix	0.0695	5.786	17.892	17.66
free	0.252	19.066	110.773	109.20

from the evaporation caused by the RF losses [11]. This pressure difference deforms the cavity geometry and shifts the cavity frequency. Since the cavity stiffening condition is hard to determine, it is necessary to perform this research under different boundary conditions at the two cavity beam ports (namely: a fully fixed condition and a completely free condition) to estimate the pressure sensitivity. During the calculation, the tetrahedron mesh with a total grid number of 1186751 is used, which can guarantee the accuracy of the analysed results. The same meshed model was used for all types of simulations to evaluate the frequency shift at the same scale. The simulated cavity deformations under one atmosphere pressure are shown in Fig. 3, which illustrate that the main frequency shift is caused by the beam port displacement. The maximum deformation is located in the middle of the outer conductor, which is near the high electric field region. According to Eq. (1), the frequency shift will decrease. The pressure sensitivities for the HWR with different boundary conditions are listed in Table 3.

During operation the boundary is dynamically balanced between the fixed and the free conditions. In this case, the pressure sensitivity coefficient, $\mathrm{d}f/\mathrm{d}P$, is between 17.66 Hz/mbar and 109.20 Hz/mbar. Because the fluctuation range of the helium bath pressure in the cryogenic plant is about ±3 mbar, according to the experience of IMP, the frequency drift will vary in the range of 53.09 Hz to 329.93 Hz, which is of the same order of magnitude as the HWR cavity bandwidth of 235 Hz. For the HWR tuner design, the tuning range and tuning resolution should be taken into account. In order to improve the pressure sensitivity coefficient $\mathrm{d}f/\mathrm{d}P$, more

efforts will be focused on adding some stiffening ribs to the cavity in the future.

3.2   Lorentz force detuning (LFD) effect

The Lorentz force is the result of the interaction between the electromagnetic field in a cavity and its RF wall current. In this circumstance, the local electromagnetic field will be redistributed. According to Eq. (1), this effect can be described by the Lorentz force detuning coefficient K_{L}:

$$K_{\mathrm{L}} = \Delta f / E_{\mathrm{acc}}^2. \qquad (2)$$

From this formula, the frequency shift Δf is proportional to the square of the accelerating gradient. The resonant frequency will correspondingly decrease with the increase of accelerating gradient. The numerical 3D analysis for
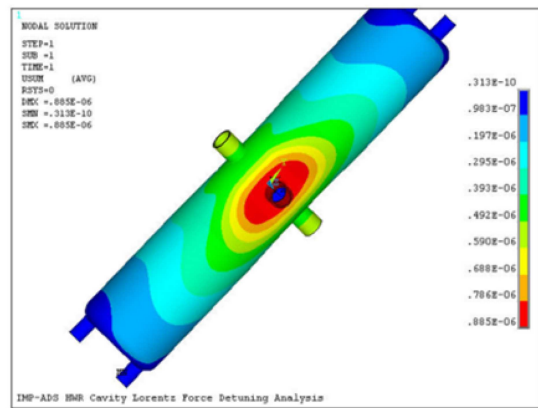

Fig. 4.   (color online) The deformation of the cavity wall caused by the LFD effect.

the LFD effect has been done and an initial simulation for the cavity with fully fixed beam pipes is shown in Fig. 4. The maximum deformation is located near the high electric field region.

The relationship between frequency shift and accelerating gradient E_{acc} is plotted in Fig. 5. According to the final fitting curve between Δf and E_{acc} in Fig. 5, the Lorentz force detuning coefficient K_{L} is -4.657 Hz/(MV/m)^2. From the point of view of energy content, the frequency detuning is still acceptable if the accelerating gradient is less than 5 MV/m. When the accelerating gradient is beyond 5 MV/m and the frequency shift is larger than -116 Hz, which is about half the frequency bandwidth, a stiffener is required.
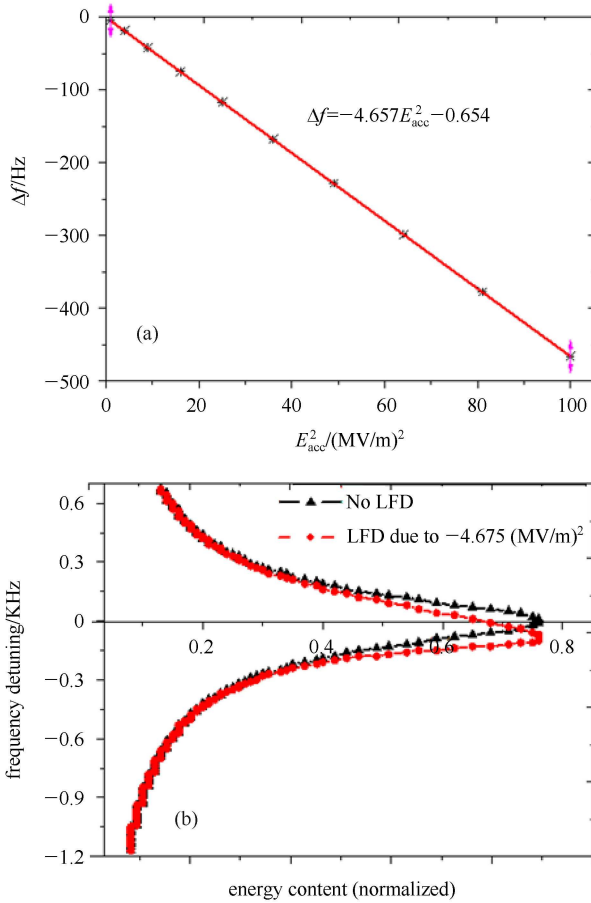

Fig. 5.   The frequency shift vs. accelerating gradient (a); the relationship between LFD ($E_{\mathrm{acc}} = 5$ MV/m) and energy content (b).

4   Tuning system

Generally speaking, we can enhance the cavity rigidity by increasing the wall thickness and reducing the frequency shift. However, this will increase the cost and is inefficient for cooling with liquid helium. Besides this method, two approaches are usually adopted, one is ex-

tra power and the other is to use a mechanical tuner. We will discuss about them separately in the following section.

Detuning affects the phase stability σ_Φ of the RF field, as in Eq. (3):

$$\sigma_\Phi = \arctan(\sigma_{\mathrm{f}}/f_{1/2}). \tag{3}$$

In this equation, σ_{f} is the rms detuning and $f_{1/2} = f_0/2Q_{\mathrm{L}}$ is the cavity half-bandwidth. Thus, the choice of Q_{L} affects the cavity field stability directly, as well as the amount of detuning σ_{f}. Furthermore, to maintain a constant accelerating voltage in HWR cavity, the RF power is required with external quality factor Q_{ext}. The optimal external quality factor to minimize the RF power is given by Eq. (4):

$$Q_{\mathrm{opt}} = \left[\left(\frac{R}{Q} \frac{I_{\mathrm{b}}}{V_{\mathrm{acc}}} \right)^2 + \left(\frac{2\Delta f}{f_0} \right)^2 + 2 \frac{R}{Q} \frac{I_{\mathrm{b}}}{V_{\mathrm{acc}}} \frac{2\Delta f}{f_0} \sin\phi_{\mathrm{b}} \right]^{-1/2}. \tag{4}$$

Here Δf is frequency detuning, ϕ_{b} is accelerating phase and I_{b} is average beam current. Fig. 6 plots the required RF power assuming optimal Q_{ext} from Eq. (4). The minimum RF power depends strongly on the cavity detuning when the effective beam current is small. Extra power is needed to meet the requirement of the designed accelerating gradient. Obviously, extra power for the compensation can be well reduced under proper pre-detuning.
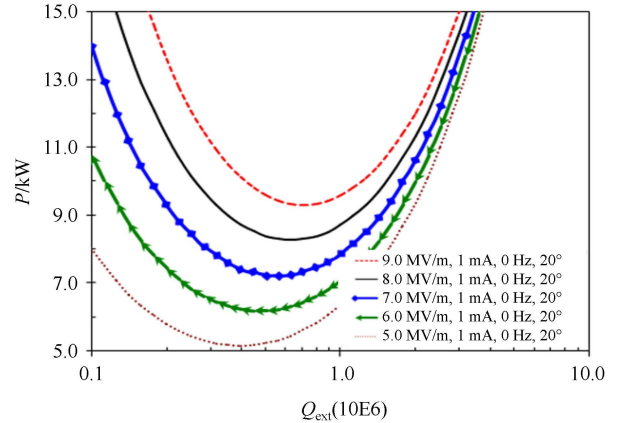

Fig. 6.   (color online) The relationship between RF power and external quality value.

Basically, there are two methods for the mechanical tuner. The first one is to mechanically deform the cavity. The other technique is to insert a probe into the magnetic or electric field of the SC cavity. The tuning method adopted by IMP is to change the length of the cells by mechanical adjustment of the overall length of the cavity, which introduces no new HOMs [12]. Fig. 7 shows the structure of the mechanical tuner for the HWR cavity.
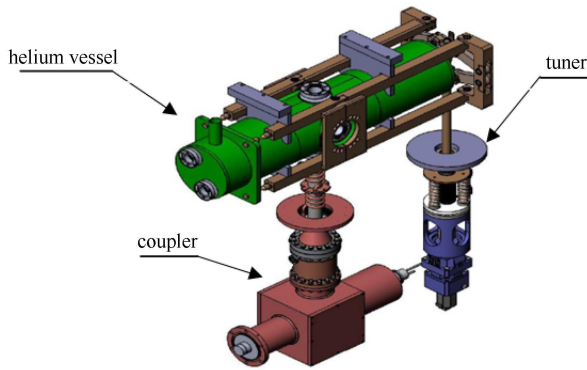
Fig. 7.   The HWR mechanical tuner structure.

The scissor jack of the tuner is mechanically mounted on the helium vessel and it will provide slow tuning. The tuner mechanism consists of four levers and twelve anti-backlash pivots, and is driven by a step motor. The main parameters obtained during the design of the tuner are listed in Table 4. Considering the fabrication tolerances and microphonics detuning of the cavity, the tuner is designed to have the ability to retune the cavity over a range of 360 kHz centered on the nominal operation frequency of 162.5 MHz. The tuning range and resolution can accommodate differences between the designed and the operated frequencies.

The mechanical tuner for HWR cavity has been manufactured and a prototype of tuner test is currently under realization at the IMP laboratory. It will be rack mounted and fully computer controlled via Low Level RF system. The tuning sensitivity is obtained by 170 kHz/mm, which is near the simulation result of 180 kHz/mm. The tuning range is about 368.9 kHz during the measurement, which meets the requirements of frequency detuning. For the fine tuning resolution, the tuner system will be installed using a piezo, which

will compensate the microphonics and LFD effect during operation. It is worth noting that the fine tuning range need to be measured in the vertical test because the quality factor is very low at room temperature and the bandwidth will be quite wide, which will cause bad interference to the fine resolution.

Table 4.   The designed parameters of the tuner system.

parameter	value
tuning sensitivity/(kHz/mm)	180
tuning force/(kN/mm)	2.2
tuning range/kHz	360
tuning resolution/Hz	9
tuning resolution step/nm	50
fine tuning range/Hz	180
backlash tolerance/Hz	<2

5   Summary

The mechanical and RF field coupled analysis of the HWR cavity has been performed at IMP. Both the helium pressure influence and the Lorentz force detuning effect, which are important and crucial reasons in the frequency detuning, are studied in this paper. A reliable tuner has been designed that meets the requirements for compensating the frequency drift due to various external sources. A prototype tuning system for experiment has recently been fabricated and will be improved in the following measurement. Stiffening ribs are supposed to be added to the cavity walls in the future in order to tune the cavity more effectively.

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