Mechanical design and analysis of a low beta squeezed half-wave resonator *

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Abstract: A superconducting squeezed type half-wave resonator (HWR) of β=0.09 has been developed at the Institute of Modern Physics, Lanzhou. In this paper, a basic design is presented for the stiffening structure for the detuning effect caused by helium pressure and Lorentz force. The mechanical modal analysis has been investigated the with finite element method (FEM). Based on these considerations, a new stiffening structure is proposed for the HWR cavity. The computation results concerning the frequency shift show that the low beta HWR cavity with new stiffening structure has low frequency sensitivity coefficient $\mathrm{d}f/\mathrm{d}p$ and Lorentz force detuning coefficient K_L, and stable mechanical properties.

Key words: HWR, mechanical stability, stiffening, FEM

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1 Introduction

The Superconducting (SC) Half-Wave Resonator (HWR) was first proposed and fabricated at Argonne National Laboratory twenty years ago [1], and since then it has become one of the best cavity geometries for applications with frequencies between 150 and 350 MHz and beam velocity beta between 0.06 and 0.4. Recently, various superconducting HWR structures, including the squeezed type [2], cylinder type [3] and taper type [4], have been developed for several proposed high-intensity light ion linac projects. In China, for the CADS (China Accelerator Driven System) project, a 162.5 MHz squeezed type SC HWR cavity with β=0.09 [5] has been designed and fabricated at the Institute of Modern Physics (IMP). Figure 1 presents the layout of the cryomodule prepared for the first test, which includes one HWR cavity together with its helium tank, two solenoids, a mechanical tuner and a main coupler.

The SC HWR cavity was constructed from pure niobium with a specified pre-processed wall thickness of 2.8 mm. Because the SC HWR cavity is highly sensitive to mechanical deformations due to its narrow bandwidth, evaluation of the frequency shift and improvements to the cavity stability must be made during cavity design. Usually, it is possible to deduce the mechanical deformations due to helium pressure, Lorentz force detuning (LFD), modal vibrations and so on, by increasing the wall thickness to enhance the cavity rigidity. However, this solution reduces the liquid helium cooling efficiency.

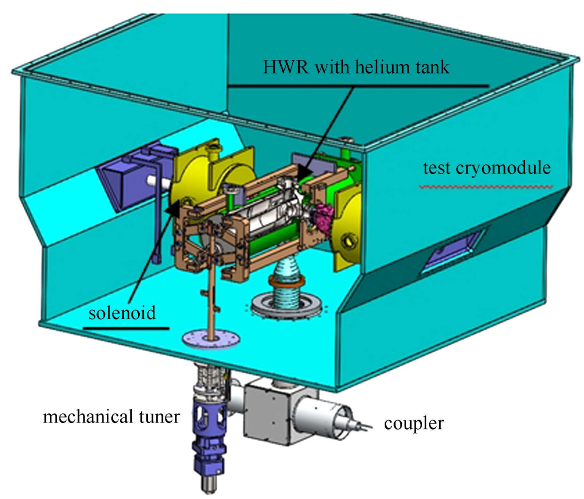

Fig. 1. (color online) Vertical view of β=0.09 squeezed type HWR cavity in test cryomodule.

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One of the most widely adopted solutions to improve the cavity stability is to install an optimized stiffening structure on the cavity.

In this paper, the basic considerations in optimizing of the stiffening structure are presented in Section 2. Based on the pressure sensitivity coefficient, the low beta squeeze type SC HWR cavity's stiffening structure design is introduced, and general comparisons between the cavities with and without stiffening structure are performed for several aspects, including Lorentz force detuning effect and mechanical resonance, based on the multiphysics calculation results with ANSYS [6] in Section 3. In Section 4, the tuning capability of the final stiffened cavity is presented. Conclusions and suggestions for future research are given in the last section.

2 Basic considerations

The wall of an SC cavity usually suffers several kinds of pressure. For example, the RF power produces radiation pressure on the cavity inside wall, while the liquid helium between the helium tank and cavity wall loads pressure on the cavity outside wall. The variation of the pressure for any reason may deform the cavity wall and cause a resonant frequency shift. In order to keep the cavity voltage constant, the RF system needs to supply surplus RF power to compensate for the cavity frequency shift. The relation between the surplus power and frequency shift is described by Eq. (1) [7].

$$P = \frac{V_{\mathrm{acc}}^2}{4\frac{R}{Q}Q_{\mathrm{ext}}}\left[\left(1+\frac{R}{Q}Q_{\mathrm{ext}}\frac{I_{\mathrm{b}}}{V_{\mathrm{acc}}}\cos\phi_{\mathrm{b}}\right)^2 + \left(2Q_{\mathrm{ext}}\frac{\Delta f}{f_0}+\frac{R}{Q}Q_{\mathrm{ext}}\frac{I_{\mathrm{b}}}{V_{\mathrm{acc}}}\sin\phi_{\mathrm{b}}\right)^2\right], \qquad (1)$$

where I_{b} is the average beam current, ϕ_{b} is the accelerating phase, f_0 is the cavity frequency, and Δf is the cavity frequency shift. It is worth noting that higher levels of detuning require more RF power for the superconducting cavity, which will greatly increase the cost of cavity operation.

The more effective method to compensate the cavity frequency shift is to minimize the frequency detuning and to employ a cavity tuner. Adding a stiffening structure is to control the frequency detuning. A good stiffening structure should have the following effects on the cavity: (i) lower helium pressure sensitivity; (ii) smaller Lorentz force detuning; (iii) lower peak stress; (iv) lower tuning sensitivity; and (v) no dangerous mechanical resonance mode. The stiffening structure design for the squeezed type HWR cavity at IMP takes those rules into account. The mechanical properties of the niobium cavity used in the analysis are listed in Table 1.

Table 1. Mechanical properties of niobium cavity.

parameters	value
Poisson's ratio	0.38
Young's modulus/GPa	105
yield strength 1)/MPa	50
yield strength 2)/MPa	140
tensile strength/MPa	400

1) Room temperature, 300 K; and 2) Low temperature, 4.2 K.

3 Cavity stiffening design

The low β squeezed type HWR cavity is characterized by a double-wall coaxial structure, with squeezed middle section of outer conductor, which makes it very compact. The stability of the HWR cavity against any external distortions is the primary design goal. However, fluctuations in the helium bath pressure are the main source of frequency detuning. Based on this consideration, a detailed mechanical design and analysis for the IMP squeezed type HWR cavity stiffening are discussed in the following section, which means minimizing the pressure sensitivity $\mathrm{d}f/\mathrm{d}p$ as much as possible by optimization.

In Fig. 2, the squeezed part in the middle of the outer conductor of the cavity is a transition from a round shape to a racetrack shape. According to the pressure vessel code and tuning study for this cavity [8], more optimization should be done in this region. From Slater's Theorem [9], removing a small volume in the high magnetic field region will decrease the inductance and increase the

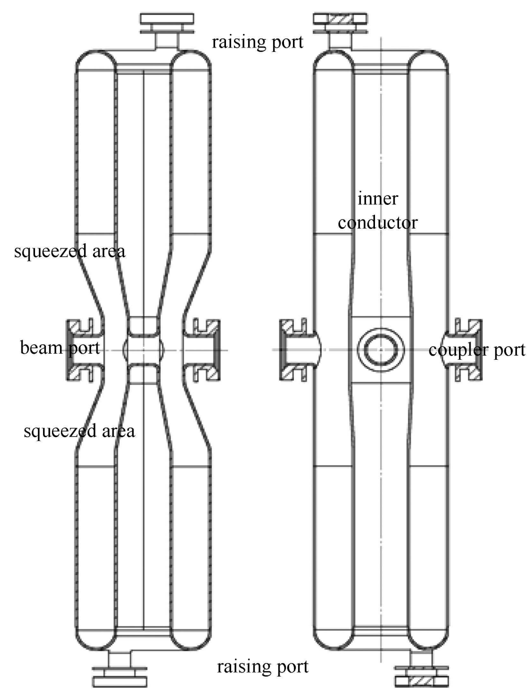

Fig. 2. (color online) Section view of IMP squeezed type HWR cavity without stiffening structure.

resonant frequency. In contrast, removing a small volume in the high electric field region will increase the capacitance and reduce the cavity frequency. The general basics of the cavity structural design are to avoid using plane surfaces in the squeezed area, as illustrated in Fig. 2.

3.1 Procedure for stiffening design

More than ten types of stiffening ribs have been analyzed to minimize the pressure sensitivity. Here, the simulation results for four of these are described in detail. For simulation accuracy considerations, the complete cavity model is employed in the simulations. The tetrahedral elements with midside nodes are applied in both structural and high frequency analysis. After solving the deformation due to pressure load, the mesh needs to be updated rather than re-meshing, which greatly improves the simulation accuracy. Fig. 3 and Fig. 4 present the deformation results with one atmospheric pressure load after adding different stiffening structures.

From simulation results of stiffening structure Ⅰ in Fig. 3, the pressure sensitivity is about 11.9 Hz/mbar, which is far below the value of the naked cavity. Considering mechanical principles, if the height of the stiffening structure is increased, the deformation will decrease correspondingly. However, the compact volume of the helium vessel limits the height of the ribs. It is worth noting that this kind of stiffening structure will save use of the much more expensive niobium, because all parts of stiffening structure Ⅰ can be fabricated from leftovers from the niobium sheet stamping process. The pressure sensitivity for both stiffening structures (Ⅱ and Ⅲ) is no better than that for stiffening structure Ⅰ. Because of the length of structure Ⅱ and the thickness of structure Ⅲ, the cost of these two stiffening structures will be significantly higher. As shown in Fig. 4, considering the large area of these two stiffening structures, a new niobium sheet will be required during fabrication of the stiffening ribs. Besides, the pressure sensitivity coefficient is not reduced greatly.

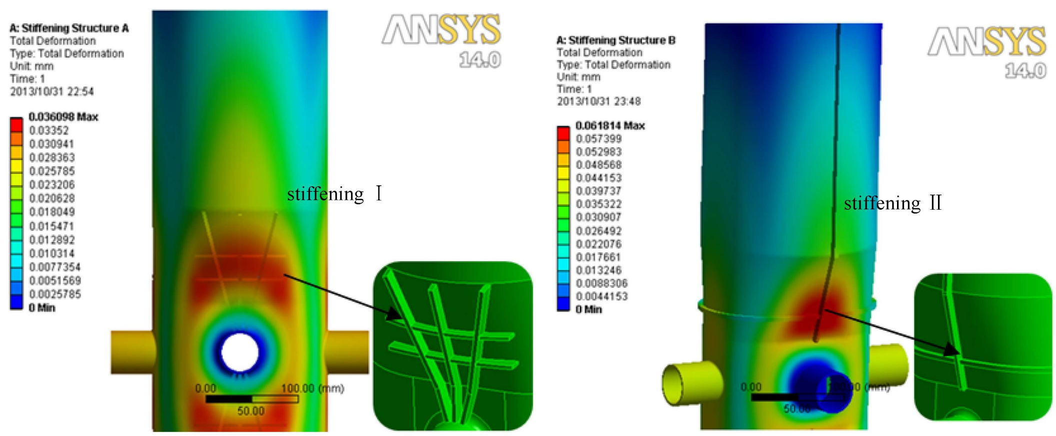

Fig. 3. (color online) The deformation results of two stiffening structures (Ⅰ and Ⅱ) for HWR cavity.

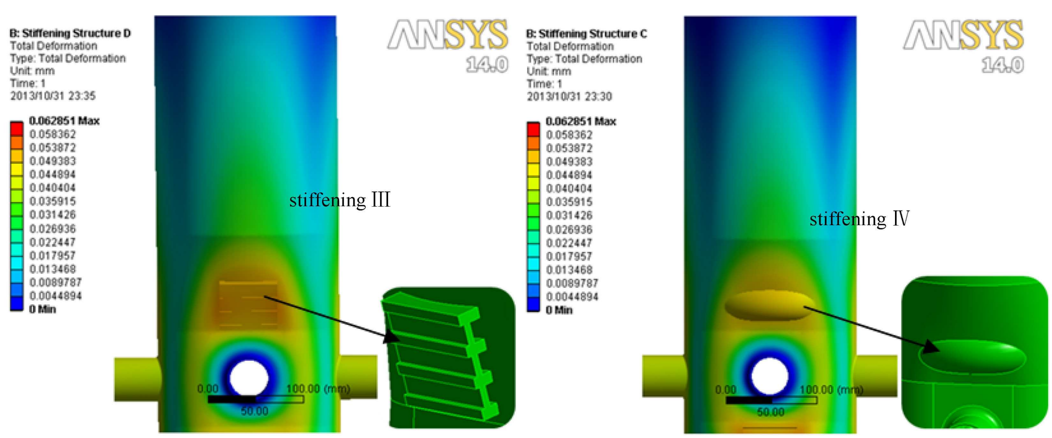

Fig. 4. (color online) The deformation results of two stiffening structures (Ⅲ and Ⅳ) for the HWR cavity.

3.2 Summary of stiffening structures

From the above simulation results, it is found that the most sensitive region is located at the squeezed part. Different stiffening ribs lead to different types of deformation in the outer conductor. Compared with the naked HWR cavity, the mechanical results for the HWR with the four stiffening structures are shown in Table 2.

As indicated in Table 2, the pressure sensitivity coefficient $\mathrm{d}f/\mathrm{d}p$ of cavity is 11.9 Hz/mbar with Stiffening Structure Ⅰ, which is significantly lower than that of the cavity with the other stiffening structures. Besides, the peak stress on the cavity with stiffening ribs decreases greatly, which could prevent the HWR cavity from plastic deformation both at room temperature and low temperature. Considering the cavity bandwidth of 235 Hz, the pressure sensitivity of 11.9 Hz/mbar can meet the requirements of the frequency tuning system. The relative simplicity of manufacturing is also one of the reasons for selecting this scheme as the final stiffening structure. A 162.5 MHz squeezed type HWR cavity with the designed stiffening structure being fabricated and its feasibility proved at the welding laboratory of Harbin Institute of Technology (HIT).

4 Mechanical resonance

Due to the high loaded quality factor, the SC HWR cavity is very sensitive to detuning. Mechanical resonances can be excited by external vibrations when the cavity is installed in the cryomodule. When the eigenmode of the mechanical resonance is close to the frequency of the external vibrations, resonance coupling may happen and cause a large deformation of the cavity. Stiffening ribs strongly affect the frequency of the mechanical resonances. Fig. 5 shows two vibration modes of the cavity with stiffening structure Ⅰ.

In modal analysis, the reported displacements do not reflect a true estimated value, rather they can indicate the relative magnitude of a structure's response at a given frequency. Therefore, the modal results focus on the fundamental frequencies and associated mode shapes [10]. In Fig. 5 on the left, the mode of vibration arises in the inner-conductor and the frequency of this mode is 172.6 Hz. For the outer-conductor vibration, in the right-hand picture, the mode frequency is about 480.9 Hz. The frequencies of the first six modes in the HWR cavity with and without stiffening structure are shown in Table 3.

The simulation results show that the mode frequencies of the cavity with a stiffening structure are higher than those of the cavity without a stiffening structure. Normally, noise intensity tends to increase as $1/f$ [11], so the lower the frequency of a mechanical mode, the easier it can be excited by an environmental source. It can therefore be concluded that Stiffening Structure Ⅰ really improves the cavity mechanical properties.

Table 2. The mechanical results of HWR without stiffening and with different stiffening under 1atm pressure load.

type of stiffening	Max disp./μm	peak stress/MPa	Δf/kHz	$(\mathrm{d}f/\mathrm{d}p)$/(Hz/mbar)	ratio*%
no stiffening	93.6	39.9	17.9	−17.7	—
stiffening Ⅰ	36.1	25.9	12.1	−11.9	32.8
stiffening Ⅱ	61.8	35.6	14.7	−14.5	18.1
stiffening Ⅲ	53.6	43.2	13.9	−13.7	22.6
stiffening Ⅳ	51.3	38.2	13.6	−13.4	24.3

*The ratio is a special value presented by the following equation: $\dfrac{|\mathrm{d}f/\mathrm{d}p_{\mathrm{stiffening}}-\mathrm{d}f/\mathrm{d}p_{\mathrm{naked}}|}{\mathrm{d}f/\mathrm{d}p_{\mathrm{naked}}}$.

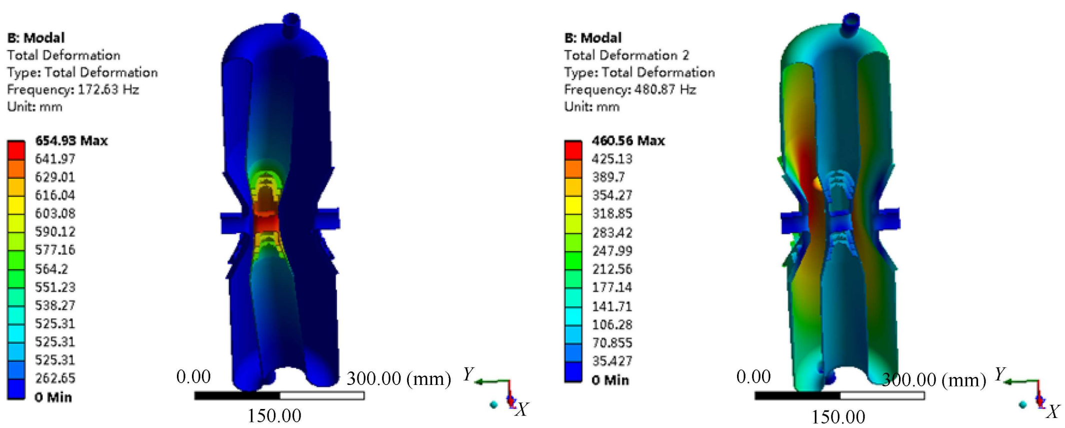

Fig. 5. (color online) Two vibration modes of HWR cavity with Stiffening Structure Ⅰ.

Table 3. The first six modes of the HWR cavity with and without stiffening structures.

mode no.	stiffening Ⅰ/Hz	no stiffening/Hz
mode 1	172.63	168.67
mode 2	258.53	242.20
mode 3	480.87	410.44
mode 4	489.28	480.13
mode 5	559.56	505.42
mode 6	593.26	550.90

5 Lorentz force detuning

With a similar procedure to the df/dp simulations, but with a pressure load calculated from the Lorentz forces in the cavity, the LFD is simulated with ANSYS. A special boundary condition is applied between two beam ports for two cases, with and without stiffening structure. The simulation results for the LFD coefficients K_L are shown in Fig. 6 for the two cases.

The boundary condition strongly influences the value of the Lorentz force coefficient. During simulations, both FEM models have been loaded with the same boundary. As expected, in Fig. 6 the Lorentz force detuning coefficient K_L for the HWR cavity with stiffening structure Ⅰ has decreased to -10.2 (MV/m)^2 compared with the coefficient for the naked cavity, -16.9 (MV/m)^2.

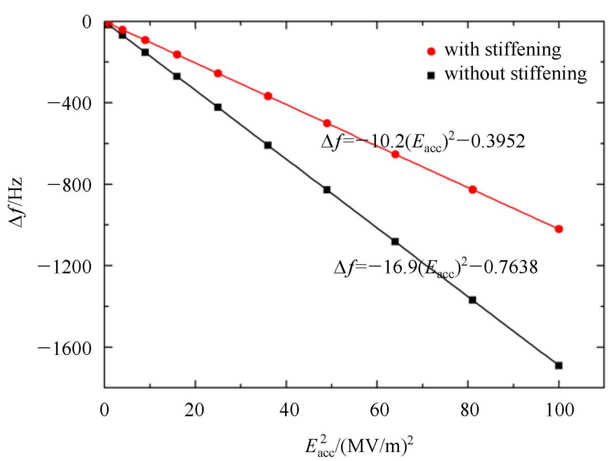

Fig. 6. (color online) The fitting curve between frequency shift and accelerating gradient.

When the Lorentz force detuning coefficient and the external quality factor are quite high, the cavity frequency will decrease with increasing accelerating gradient. If the HWR cavity is operated off resonance frequency, the magnitude of its amplitude and phase deviations is correlated, and it depends on its loaded Q and the magnitude Δf of the frequency deviation. In a complex representation the cavity field V as a function of Q_L and Δf is given by Eq. (2) [12].

$$V=V_0/(1+j\cdot 2Q_L\Delta f)=V_0/(1+j\cdot\tan\Delta\varphi), \tag{2}$$

and the amplitude and phase deviations are

$$|\Delta V|=V_0-|V| \tag{3}$$

and

$$\Delta\varphi=\tan^{-1}2Q_L\Delta f \tag{4}$$

respectively.

In order to keep V equal to V_0, the following corrections to V have to be applied, using Eq. (5).

$$V_0=V\cdot e^{j\Delta\varphi}/\cos\Delta\varphi=V\cdot(1+j\cdot\tan\Delta\varphi). \tag{5}$$

Normalizing the accelerating field or energy gain like Eq. (6),

$$V^2(\Delta\varphi)=\frac{1}{1+\tan^2(\Delta\varphi)}, \tag{6}$$

we finally get the frequency detuning as in Eq. (7), which is shown as a curve in Fig. 7. In this equation, G_{mes} is the cavity accelerating gradient.

$$df(\Delta\varphi,Q_L,G_{mes},K_L)=\frac{f_0}{2Q_L}\tan(\Delta\varphi)+K_LG^2_{mes}\cos^2(\Delta\varphi). \tag{7}$$

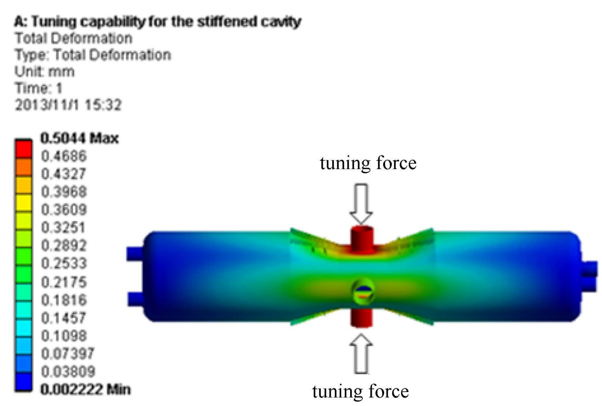

Fig. 7. (color online) The relationship between LFD (E_{acc}= 4.22 MV/m) and energy content.

Figure 8 illustrates the relationship between LFD and the square of the cavity voltage for both structures during the simulation. The curve is not just for the cavity itself but for the superconducting RF control system including the cavity coupling, mechanical tuner and klystron in a closed control loop. In order to control the cavity at Master Oscillation (MO) frequency and at a fixed gradient, the cavity needs to be retuned along half of the curve during operation. Finally the value deviating from the Y axis is the cavity frequency detuning at a specific time. The vertical axis is the square of the cavity voltage, or the cavity stored energy (normalized). The stiffening structure gives a low LFD coefficient and the frequency shift has been reduced greatly by adding the new stiffening structure.

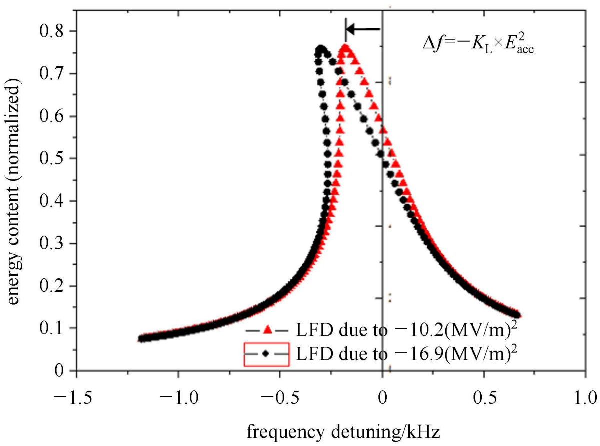

Fig. 8. (color online) Tuning simulation result for the stiffened cavity.

6 Tuning capability of the stiffened cavity

A mechanical tuner mounted on the helium vessel will provide both fast and slow tuning for the cavity to change its fundamental resonance frequency. The tuning capability of the stiffened HWR cavity is identified in Fig. 8. According to the properties in Table 1 and the tuning simulation, the tuning range and tuning sensitivity are as shown in Table 4.

A preliminary goal of 362.40 kHz full tuning range has been chosen for the cavity frequency tuning. This tuning range provides a comfortable safe margin for the operational offset. The tuning sensitivity has been increased from 180 kHz/mm to 199.12 kHz/mm after adding the stiffening structure.

Table 4. Tuning capability of the stiffened HWR cavity.

parameter/unit	value
tuning sensitivity/(kHz/mm)	199.12
coarse tuning range/MHz	362.40
tuning force/(kN/mm)	2.01
fine tuning range/Hz	300
Max. tuning deformation/mm	1.82

7 Summary

The CADS Injector-Ⅱ high current superconducting RF linac requires a low beta HWR cavity operating at high loaded quality factor to reduce cost and maximize operational efficiency. The HWR cavity therefore needs to have good mechanical stability and small sensitivity coefficients. Although an unstiffened cavity is easier to manufacture than a stiffened one, it will be more fragile during handling and its low mechanical resonances frequency will limit the bandwidth. In this paper, several methods are presented to reduce pressure sensitivity through optimization of the squeezed part of HWR cavity. For the continuous wave superconducting linac at IMP, a squeezed type HWR cavity is being fabricated at HIT to investigate the optimized stiffening structure. Considering the great improvement brought about by the stiffening structure in terms of the stable mechanical properties, such as LFD and mechanical resonance, a novel taper type half-wave resonator should be investigated in the future to further increase both the mechanical stability and the RF performance.

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