Structural analysis of quarter-wave resonators in IMP *

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Abstract: The taper-shaped superconducting quarter wave resonators with frequency of 80.5 MHz, β of 0.041 and 0.085 have been pre-researched. The radio frequency (RF) design of the cavities has been completed, and the structural design is also an important aspect which will be discussed in the following. The frequency shift caused by the etching effects of the surface treatment, the helium bath pressure and the Lorentz force, and the mechanical modes caused by the microphonic excitation have been analyzed. The results show that the frequency variation from the Lorentz force is not serious and stiffening rings are explored aimed at decreasing the deformation brought by the helium pressure and microphonic excitation.

Key words: quarter-wave resonator, structural stability, etching effect, Lorentz force detuning, helium pressure detuning, mechanical vibration

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1 Introduction

A typical loaded Q of superconducting cavities is chosen to be a few 10^6, and the resulting narrow bandwidth makes superconducting cavities very sensitive to these factors which may lead to a shift in the resonant RF frequency. A stable resonant frequency for the superconducting cavity is desired, because excessive frequency fluctuations require extra power to control the RF amplitude and phase. The reasons that lead to frequency fluctuations include the fluctuations in the liquid helium pressure, Lorentz force detuning, mechanical vibrations and the etching effects. Since the operating temperature for the QWR cavities is 4.5 K, the helium pressure stability will be determined by the extent to which the cryogenic plant can be controlled. The stiffening measures are intended primarily to reduce the pressure sensitivity.

2 Mechanical simulations

The ANSYS codes were used for the simulations [1]. We assumed the same mechanical properties for the cavity walls and connecting (stiffening) rings (Young modulus=105000 N/mm^2 and Poisson ratio ν=0.38) [2].

2.1 Etching effects

In order to obtain a high performance superconducting cavity, the surface treatment is an important step. Either the BCP or the EP is to etch the proper thickness of the inner surface, which will change the frequency. According to Slater's perturbation theory, a small deformation in the cavity boundary will lead to a frequency shift:

$$\frac{\delta\omega_V}{\omega_V}=\frac{1}{4\bar{U}}\int_{\delta V^*}(\epsilon_0E^2-\mu_0H^2)\mathrm{d}V, \qquad (1)$$

where,

$$\bar{U}=\frac{1}{4}\int_{V}(\epsilon_0E^2+\mu_0H^2)\mathrm{d}V,$$

is the average energy stored in the cavity volume V and δV^* is the volume variation caused by the distortion at the cavity wall.

Using the ANSYS-APDL code, the change in the frequency because of the etching can be calculated. Firstly, the electro-magnetic field distribution has to be simulated, and then the frequency change caused by varying the cavity wall's thickness can be obtained (Fig. 1). It can be seen that, for QWR cavity, the etching of the internal surface will increase the resonant frequency of the cavity, and the smaller the cavity inner space, the larger the frequency increment the etching will lead to. The simulation results show that 1 μm etching thickness will lead to 0.4 and 0.24 kHz increase in the frequency of QWR-0.041 and QWR-0.085, respectively.

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2.2 Lorentz force detuning

The Lorentz force on the cavity surface is caused by the interaction of the surface electromagnetic fields with the induced surface currents [3]. This pressure results in a deformation of the cavity walls, changing the cavity volume by ΔV, which will cause the shift in the resonant frequency by Formula (1). This shift is often quantified by K_{L} which is defined as:

$$K_{\mathrm{L}}=\frac{\mathrm{d}f}{\mathrm{d}E_{\mathrm{acc}}^2}. \tag{2}$$

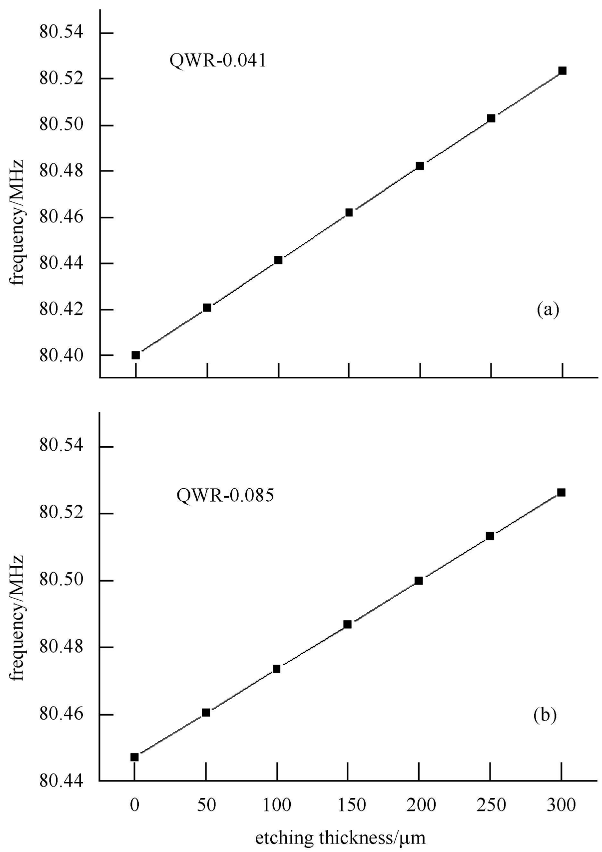

Fig. 1. Quantitative dependence of the resonant frequency of the cavity on the etching thickness for QWR-0.041 (a) and QWR-0.085 (b).

Table 1. Simulation results of Lorentz force's function on the resonant frequency.

cavity	voltage/MV	$K_{\mathrm{L}}=\mathrm{d}f/\mathrm{d}E_{\mathrm{acc}}^2/(\mathrm{Hz}/(\mathrm{MV/m})^2)$
QWR-0.041	1	−0.43
QWR-0.085	2	−0.62

If the cavity works in the continuous wave mode, then the frequency change will be invariant, it is the static Lorentz force detuning; otherwise, when the cavity works in the pulsed wave mode, the dynamic Lorentz force detuning will be caused. In this paper, only the static situation was considered. Fig. 2 shows the deformation caused by the Lorentz force for the QWR-0.041 and QWR-0.085 at their working voltages. From the data in Table 1, it can be calculated that the working voltage of 1 MV and 2 MV will lead to −6.4 Hz and −31.2 Hz for the two cavities, respectively.

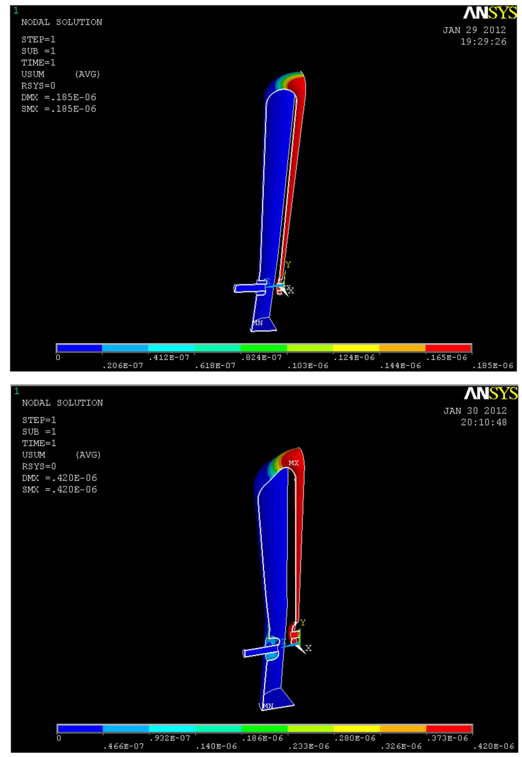

Fig. 2. (color online) Deformation of the QWR-0.041 caused by Lorentz force at V_{acc}=1 MV (top) and the QWR-0.085 caused by Lorentz force at V_{acc}=2 MV (bottom).

2.3 Helium pressure detuning

The structural simulation for the helium bath pressure effect was modeled with a constant pressure on the outside of the cavity wall, and the shift in the resonant frequency (Δf) with changing ambient pressure (Δp), which satisfies a linear relationship, was obtained. Fig. 3 presents the deformation caused by 1 atm. pressure on the QWR-0.041 and QWR-0.085 cavities, and Table 2 shows the simulation results of the helium pressure's effect on the naked cavities, from which we can see that the frequency shifts of the unstiffened cavities caused by the helium bath pressure are not small enough, so relevant stiffening measurements should be explored.

$$\mathrm{d}f\propto\mathrm{d}p. \tag{3}$$

Table 2. Simulation results of helium pressure's function on the resonant frequency.

cavity	$\mathrm{d}f/\mathrm{d}p$/(Hz/mbar)
QWR-0.041	−16.94
QWR-0.085	−23.29

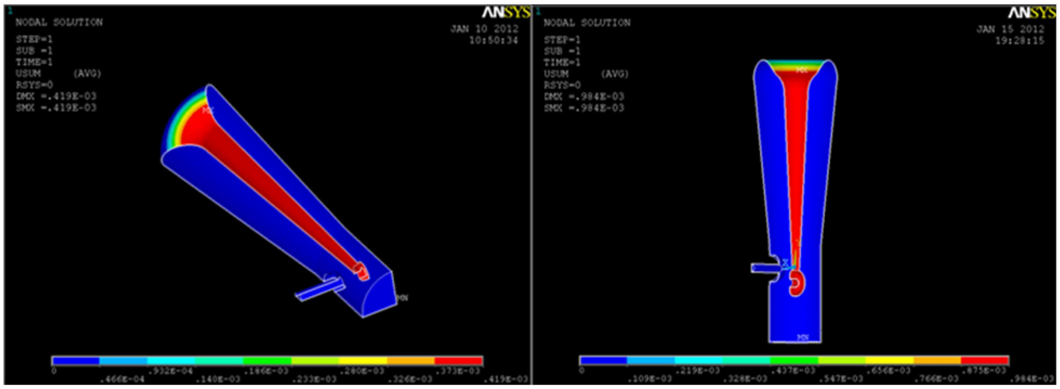

Fig. 3. (color online) Deformation of the QWR-0.041 and QWR-0.085 caused by 1 atm pressure.

Table 3. Simulation results of helium pressure's function on the resonant frequency for ring-stiffened QWRs.

QWR(β=0.041)	ring-height=3 mm	ring-height=5 mm	ring-height=10 mm
Max-displacement@1 mbar/μm	0.0266	0.0267	0.0288
df@1 mbar/Hz	−13.02	−13.30	−14.26
QWR(β=0.085)	ring-height=3 mm	ring-height=5 mm	ring-height=10 mm
Max-displacement@1 mbar/μm	0.0474	0.0474	0.0481
df@1 mbar/Hz	−14.24	−14.31	−14.69

In order to improve the stiffness of the cavity, a ring was added on the short plate (Fig. 4). Rings with different heights, thicknesses and radii will lead to different stiffening effects. To simplify, only various heights of rings were studied to test their efficiency on strengthening in this paper. The simulation results show that the stiffening ring is very effective in increasing the structural stability, but the higher the ring, the worse the reinforcement effect (Table 3).

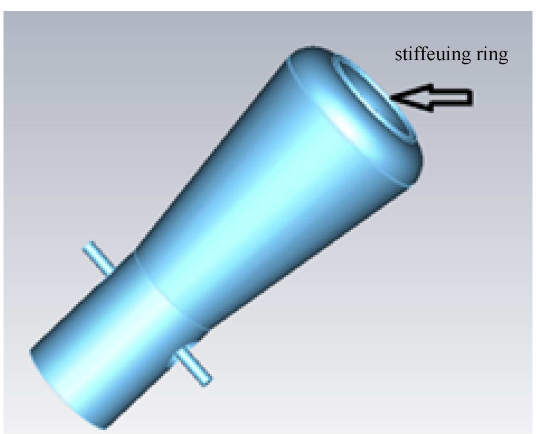

Fig. 4. Stiffening ring on the short plate of the QWR cavity.

2.4 Mechanical vibrations

A mechanical wave in the environment can be transmitted to the cavity by various media, and the cavity can resonate mechanically at certain frequencies. Particularly for the QWR cavities, the vibration of the inner conductor can cause large deformation which is usually too fast to be recovered by mechanical tuners. Model analysis of the resonators was done both for the unstiffened and stiffened cavities. Fig. 5 presents the lowest three vibration modes for the naked cavities.

Table 4. The mechanical frequencies of the three lowest vibration modes for QWR-0.041 and QWR-0.085 naked cavities.

MODE	QWR-0.041	QWR-0.085
MODE1/Hz	33.7966	35.5601
MODE2/Hz	33.8041	35.5733
MODE3/Hz	79.8079	96.3520

From the data of Table 4, we can see that the frequencies of the lowest vibration mode for the two cavities are too low. The lower the frequency, the easier an environmental source that excites it can be found, besides, noise intensity tends to go as $1/f$. 50 Hz is very bad because it is the frequency of the electrical power network in China, so that one can find noise of this frequency everywhere. The same stiffening method as the case of weakening the helium pressure effect was used since it is necessary to improve the frequency of mechanical vibration above 50 Hz, and similar simulation results have been gained (Table 5).

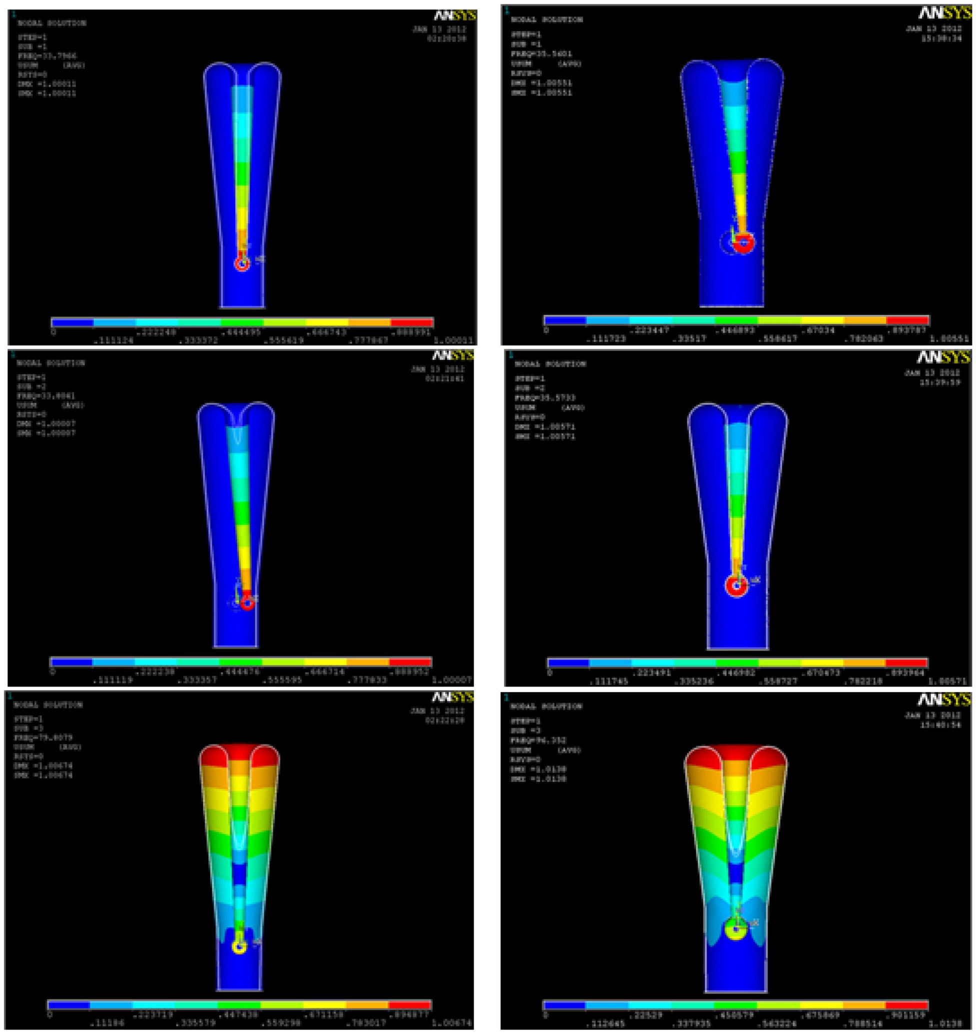

Fig. 5. (color online) The lowest three vibration modes for QWR-0.041 (left) and QWR-0.085 (right) naked cavities.

Table 5. The mechanical frequencies of the three lowest vibration modes for QWR-0.041 and QWR-0.085 ring-stiffened cavities.

ring-height/mm	QWR(β=0.041)			QWR(β=0.085)		
	MODE1/Hz	MODE2/Hz	MODE3/Hz	MODE1/Hz	MODE2/Hz	MODE3/Hz
3	69.0139	69.1835	216.103	79.9614	80.1215	204.498
5	68.8961	69.0639	216.085	80.0980	80.2369	204.561
10	68.4518	68.5010	216.040	79.8063	79.9764	204.842

3 Analysis of the simulation results

Ideally, superconducting cavities having quality factors $Q_0 > 10^8$ typically for QWRs require very little RF power to generate the accelerating gradient. Some power is demanded for beam acceleration and control of microphonics. However, if the cavity resonant frequency shifts away from the generator frequency, additional RF power is required to maintain the amplitude and phase of the acceleration field. Assuming that the power of the generator is twice the beam power, and in the case of beam current with 2 mA, the QWR-0.041 and QWR-0.085 can be detuned over a bandwidth of 54 and 115 Hz, respectively.

In operation, 1 atm. helium bath pressure will cause −13 kHz and −14 kHz frequency shift for QWR-0.041 and QWR-0.085, respectively, so, if the cryoplant system cannot be maintained as stable, a fast tuner is needed in the feedback loop.

As for the evaluation of the microphonics, here we should start from the decay time of the beam loaded cavity. The loaded quality factor:

QWR-0.041: Q_L=2.5×10^5, QWR-0.085: Q_L=6.6×10^5.

The decay time of the cavity relevant with Q_L:

$$\tau=\frac{Q_L}{\omega}.$$

QWR-0.041: τ=0.003 s, QWR-0.085: τ=0.008 s.

The period of the lowest vibration mode:

QWR-0.041: $\tau_{\text{microphonics}}$=0.014 s, QWR-0.085: $\tau_{\text{microphonics}}$=0.0125 s.

Since the period of the microphonics is longer than the cavity decay time, the stem vibration course will cause the superconducting QWR cavity to be lost; focusing on this problem, additional means should be taken to raise the frequency of the microphonics for the sake of avoiding the cavity getting lost before a microphonic movement completion.

4 Conclusions

Numerical models have been used to predict the stiffness of the superconducting QWR cavities and to design the stiffening elements for them. The simulation results show that the cavities without any stiffening measures cannot resist the helium pressure impacts and microphonic excitations sufficiently while a stiffening ring on the short plate can increase the rigidity of the structures significantly. In the later work, the helium vessel will be designed to further improve the mechanical stabilities of the resonators.

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