Mechanical analysis of a $\beta = 0.09$ 162.5MHz taper HWR cavity

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Abstract: One superconducting taper-type half-wave resonator (HWR) with frequency of 162.5MHz, of 0.09 has been developed at Peking University, which is used to accelerate high current proton ($\sim 100$mA) and $D^+$ ($\sim 50$mA). The radio frequency (RF) design of the cavity has been accomplished. Herein, we present the mechanical analysis of the cavity which is also an important aspect in superconducting cavity design. The frequency shift caused by bath helium pressure and Lorenz force, and the tuning by deforming the cavity along the beam axis will be analyzed in this paper.

Key words: HWR, tuning, Lorentz force detuning, helium pressure detuning

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1 Introduction

More and more projects based on high current proton and deuteron linear accelerators are proposed and emerged to support various fields of science like particle physics, nuclear physics, and neutron-based physics. Superconducting RF (SRF) technology is mandatory for high current continuous wave (CW) proton and deuteron linear accelerators. HWR is one of the best cavity geometries for the acceleration of high-intensity proton and heavy ion beams in low beta range. Compare to the Quarter-Wave Resonator (QWR), HWRs have no dipole fields on the beam axis due to the symmetry of EM fields and better mechanical properties. Recently, various superconducting HWR structures have been developed, of which the taper type HWR has good mechanical stability and lower maximum surface fields in comparison to the squeezed type. Ring-shaped center conductor of taper type HWR is proposed by Argonne National Laboratory [1]. Compared to the race-track geometry, it has not only much lower peak surface magnetic field and significantly higher shunt impedance, but also no quadrupole electric field component, which is very important for high current beam acceleration.

One superconducting taper type HWR with frequency of 162.5MHz, $\beta$ of 0.09 has been developed at Peking University. This cavity is designed to accelerate 100mA proton beam or 50 mA deuteron beam. The structure of the cavity is shown in Fig. 1. The EM design of the cavity has been accomplished and the main RF parameters are shown in Table 1. The diameter of the beam pipe of the cavity is 40 mm. In this paper, we present the structural analysis of the cavity. The frequency shift caused by bath helium pressure and Lorenz force, and the tuning by deforming the cavity along the beam axis will be analyzed.

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

| Parameter | value |
|-----------|-------|
| frequency/MHz | 162.5 |
| $\beta$ | 0.09 |
| $B_{\text{peak}}/E_{\text{acc}}/(\text{mT}/\text{MV/m})$ | 6.4 |
| $E_{\text{peak}}/E_{\text{acc}}$ | 5.3 |
| $R/Q_0/\Omega$ | 255 |
| $G/\Omega$ | 39.0 |

2 Helium pressure detuning

When the cavity frequency shifts from the resonance frequency, the cavity stored energy degrades, and the accelerating field decreases, thus causes the instability of cavity operation. Moreover, the cavity detuning brings higher requirements for both RF control and RF power level. Microphonics and Lorentz force detuning are the main factors for cavity detuning. The fluctuations of the liquid helium bath pressure are the main source of microphonics. The pressure sensitivity coefficient, $df/dp$, is used to characterize the influence of the helium pressure variation on the detuning of the cavity. Larger $|df/dp|$ may cause serious cavity detuning and instability of cavity operation. The mechanical design of the SRF cavity needs to have a lower $|df/dp|$.  

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The ANSYS codes [2] were used for the simulation. The model was meshed in ANSYS-Workbench and the simulation was done in ANSYS-APDL. The finite element mesh generation is tetrahedrons, and we used local mesh refinement scheme in the high field region. The simulation for the helium pressure detuning was modeled with a series of constant pressure on the surface of the cavity shell. The properties of niobium used in the simulation are list in Table 2.

| Parameter                  | Value |
|----------------------------|-------|
| Poisson’s ratio            | 0.38  |
| Young’s modulus/GPa        | 105   |
| Tensile yield strength/MPa | 250   |
| Thickness/mm               | 3.0   |

Different boundary conditions at different ports are taken consideration. There are three kinds of ports, seen in Fig. 1 (a), port 1 is the beam port, port 2 is the coupler port and port 3 is the cleaning port. Fixed boundary condition and free condition were put on the three kinds of ports. During operation the boundary condition is close to fixed.

As we known, when a small volume in the high magnetic field region was removed, the equivalent inductance will decrease and the resonant frequency will increase. In constant, removing a small volume in the high electric field will increase the equivalent capacitance and reduce the resonant frequency.

The simulation result is shown in Table 3. From the simulation result we can see that $df/dp$ is -31.5 Hz/mbar when all the three kinds of ports are at free boundary conditions. It means that the deformation in the high electric field plays a major role in the frequency detuning. The deformations under one atmosphere pressure are shown in Fig. 2. When the beam port is free, the maximum deformation locates in the beam pipe region, which is in the high electric region. When the beam port is fixed, the maximum deformation locates in the short end of the cavity, which is in the high magnetic field region, and $df/dp$ is 3.11 Hz/mbar in this case.

| Port 1 | Port 2 | Port 3 | $df/dp$ (Hz/mbar) |
|--------|--------|--------|-------------------|
| free   | free   | free   | -31.5             |
| fixed  | free   | free   | 3.11              |
| fixed  | fixed  | free   | 3.18              |

The typical value of $df/dp$ is about 30 Hz/mbar for 1.3GHz elliptical cavity [3] and it can be as high as 74 Hz/mbar for medium beta elliptical cavity with the thickness of 5mm [4]. The typical $df/dp$ is about -10 Hz/mbar for spoke cavity with radial stiffening ribs [4]. The frequency shift caused by changing the helium pressure is about -17.6 Hz/mbar for a squeezed HWR cavity [5]. The pressure sensitivity coefficient is only about 3 Hz/mbar for this taper type $\beta=0.09$ HWR cavity without stiffening rings. This verifies that taper type HWR cavity has good mechanical properties against pressure detuning.
By adding stiffening ribs on the short end of the cavity, the $df/dp$ can decrease further to 0.01 Hz/mbar when the beam port is fixed. The structure of the stiffening ribs is shown in Fig. 3. Such low $|df/dp|$ is very good for cavity operation.

3 Lorenz force detuning

Another factor for cavity detuning is Lorentz force. The Lorentz force is the result of the interaction between the rf magnetic field in a cavity and the rf wall current. The radiation pressure,

$$P_L \propto \mu_0 H^2 - \varepsilon_0 E^2$$

causes a small deformation of the cavity shape leading to a change in the resonant frequency:

$$\Delta f \propto (\mu_0 H^2 - \varepsilon_0 E^2) \Delta V$$

Here $\Delta V$ is the change in the volume of the cavity region. Under steady-state condition this detuning is proportional to the square of the electrical field.

The Lorenz force detuning coefficient $K_L$ is used to describe this effect which is defined as

$$K_L = \Delta f / E_{acc}$$

Here $\Delta f$ is the frequency shift and $E_{acc}$ is the average accelerating electric field. From Eq. (1) we can see that the direction of the Lorenz force in the electric region and in magnetic region are opposite which resulting the $K_L$ a negative value.

The deformation of the cavity wall with free beam ports is shown in Fig. 4 (a) and the maximum deformation locates near the high electric field areas. The relationship between frequency shift and the square of the electrical field is plotted in Fig. 5. According to the fitting curve, the Lorenz force detuning coefficient $K_L$ is $-5.55$ Hz/(MV/m)$^2$, and $K_L=-0.41$ Hz/(MV/m)$^2$ when the beam ports are fixed. Simulation results show that the taper type HWR cavity also has very low $|K_L|$, which is good for cavity pulse operation.

4 Tuning analysis

Mechanical tuning method is used to compensate the frequency detuning, and the tuning fore is applied along the beam line, as shown in Fig. 6.
The simulation result shows that the tuning sensitivity is -253 KHz/mm when the cavity was squeezed or stretched along the beam line. The displacement is relative to the center of the cavity. The maximum displacement is about 0.7 mm considering the safe factor larger than 1.1. In this case, we think the niobium is still in the range of elastic deformation. In Table 4, we list the displacement and the safe factor. Safe factor 1 is considering the max equivalent and the safe factor 2 is considering the max shear stress. Therefore, the tuning range for the HWR cavity is ±177KHz.

Table 4. The displacement and the safe factor.

| Displacement/mm | Safe factor 1 | Safe factor 2 |
|-----------------|--------------|--------------|
| 0.75            | 1.19         | 1.04         |
| 0.70            | 1.27         | 1.12         |
| 0.65            | 1.38         | 1.21         |

5 Summary

Mechanical analysis is important for the cavity design. Both the helium pressure detuning and the Lorentz force detuning are studied in this paper. The simulation result shows that this taper type HWR cavity has better mechanical stability against the helium pressure fluctuation and Lorentz force detuning than the elliptical cavity, spoke cavity and even better than the squeezed type HWR cavity. The tuning analysis of the HWR cavity was also done, which will provide reference for the design of tuner.

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