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MULTI-PHYSCIS DESIGN STUDIES OF A SUPERCONDUCTING QUARTER-WAVE RESONATOR AT PEKING UNIVERSITY*

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Abstract

A 81.25MHz, geometric beta=0.046 quarter-wave resonator has been designed and analysed at Peking University. This paper mainly presents the multi-physics studies of this cavity, include electromagnetic design, mechanical analysis and multipacting simulation, to predict its behaviour under practical operating process. Various transverse vibration modes of inner conductor were found under different fixed conditions and an asymmetric shorting plate was adopted to avoid high possibility of multipacting.

INTRODUCTION

There's presently a growing amount of CW high current heavy-ion linear accelerator facilities based on superconducting technology to better support various field of science [1]. Based on that, we designed a quarter-wave resonator for the demand of low beta high current cavity. Structural design is an important aspect overall cavity and cryomodule implementation. Because of the asymmetric geometry of the cavity and usually a long pendulous inner conductor, the thin-wall structure of QWR cavity can be easily deformed by the impact of various fluctuations, causing resonant frequency shift. Excessive frequency shift require additional RF power to control the RF amplitude and phase [2]. Thus a stable resonant frequency is required. We did a sequential coupled field simulations to predict the behaviour of the naked cavity under practical operation, several coupled field analysis were carried out. For the issue of multipacting, an asymmetric shorting plate was adopted to lower the possibility of multipacting.

RF DESIGN

The model of 81.25 MHz QWR is shown in Fig. 1, it is designed and optimized in CST MWS [3]. Taper-shape inner and outer conductors can improve the RF performance relative to using straight cylinders [4]. The top and bottom four ports are used for rinse and the bottom two are also used for power coupler and pick up. All ports are located at a proper position that the water pipes can go deep into the cavity, at the meanwhile they won't influence the surface peak electromagnetic field as shown in Fig. 1. In addition, donut-shaped drift tube was adopted to reduce the magnetic field in the gap [5]. Additional methods to supress the beam steering effect have been studied.

The main geometry and RF parameters of this cavity are summarized in Table 1.

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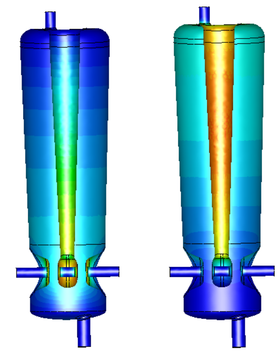

Figure 1: Magnetic field distribution (left) and electric field distribution (right) for the 81.25 MHz mode.

Table 1: The Main Parameters of 81.25 MHz QWR. Surface Resistance was Assumed to be 25nΩ @4.5K in the Calculation

Frequency[MHz]	81.25
β_g	0.046
G[Ω]	21
R_{sh}/Q[Ω]	592
Q_0	8.4e8
Epk/Eacc	4.9
Bpk/Eacc[mT/(MV/m)]	6.4
Beam aperture[mm]	34
Cavity height[mm]	980
Cavity diameter[mm]	270

MECHANICAL SIMULATION

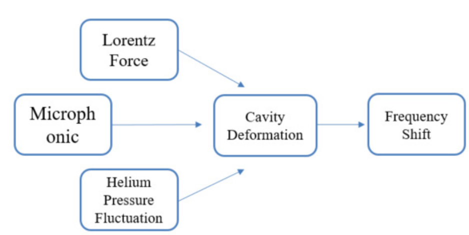

Figure 2: Multi-physics field coupling with cavity.

As shown in Fig. 2, cavity deformations from cooling down, Lorentz force, Helium Pressure Fluctuations (HPF) and microphonics can lead to resonant frequency change, the prediction of the resonant frequency change depends on the accuracy of the calculated electromagnetic fields as well as the calculated mechanical deformation. Due to the asymmetric structure with four ports, we used the whole structure to do the simulation.

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To predict the frequency change, in general, we need two models: high frequency vacuum model to calculate the frequency before and after the cavity deformed, and a shell structure model to evaluate the displacement field distribution after applying loads. Thus corresponding two solvers are needed, Eigenmode Solver and Mechanical Solver. Actually, the displacement is very small compared to the scale of cavity, so we used sensitive analysis in Eigenmode Solver to evaluate the frequency change with more efficiency. In this way, we don't have to establish a totally new deformed structure but by importing the displacement field distribution to the original model in Eigenmode Solver, the frequency change due to the displacement field can be evaluated by using derivative information and no real deformation is applied to the structure or the mesh.

LORENTZ FORCE DETUNING

Using the vacuum model of QWR cavity we simulated the RF field distribution at 81.25 MHz for the accelerating mode-see Fig. 1

The distribution of Lorentz force density applied to the walls of cavity can be calculated as follows:

$$\vec{F} = \frac{1}{4}(\mu|\vec{H}|^2 - \varepsilon|\vec{E}|^2) \cdot \vec{n}$$

and the Lorentz force detuning coefficient is:

$$K_L = -\frac{\Delta f}{{E_{acc}}^2}$$

K_L is a constant. We calculated the frequency change in a range of accelerating gradients, result shows that the LFD coefficient, $K_L = -5.296\text{Hz}/(\text{MV/m})^2$.

HELIUM PRESSURE FLUCTUATION AND MICROPHONICS

Superconducting cavities operate at a low temperature by immersed in liquid helium, thus pressure fluctuations in the liquid helium will be transmitted to cavity wall, leading to cavity deformation and resonant frequency shift. We use df/dp to characterize the frequency sensitivity to the helium pressure fluctuation. In our simulation, a constant pressure P=0.1MPa was applied to the outside of cavity wall. We studied the effects of various fixed condition to df/dp. See Table. 2

Table 2: df/dp Under Various Fixed Condition

	Port1	Port2	Beam pipe	df/dp(Hz/mbar)
1	DOF	Free	Free	-18
2	Free	DOF	Free	-27
3	Free	Free	DOF	-15
4	DOF	DOF	Free	-4.8
5	DOF	Free	DOF	-4.97
6	Free	DOF	DOF	-15
7	DOF	DOF	DOF	-4.1

In practical operation, the constraints fall in between all ports fixed and totally free, so the value of df/dp is between -27~-4.1.

Because of the long pendulous inner conductor and the thin-wall structure, quarter-wave cavities have a pair of degenerate mechanical eigenmodes, with relatively low frequency ~30-60 Hz [6], which may be excited by the low frequency helium pressure fluctuation. This can be simulated in ANSYS WORKBENCH Modal and Harmonic Response systems [7]. We set the helium pressure fluctuation amplitude at ±10mbar [8], the results of frequency response spectrum caused by the HPF under various constraints are as follows (Fig. 3). Static helium pressure cause inner conductor sink in vertical direction, and dynamic helium pressure fluctuation may cause inner conductor vibration in transverse dimension. Without any port fixed, the lowest mechanical vibration mode frequency is about 31 Hz with a wide bandwidth, and when some ports are fixed,

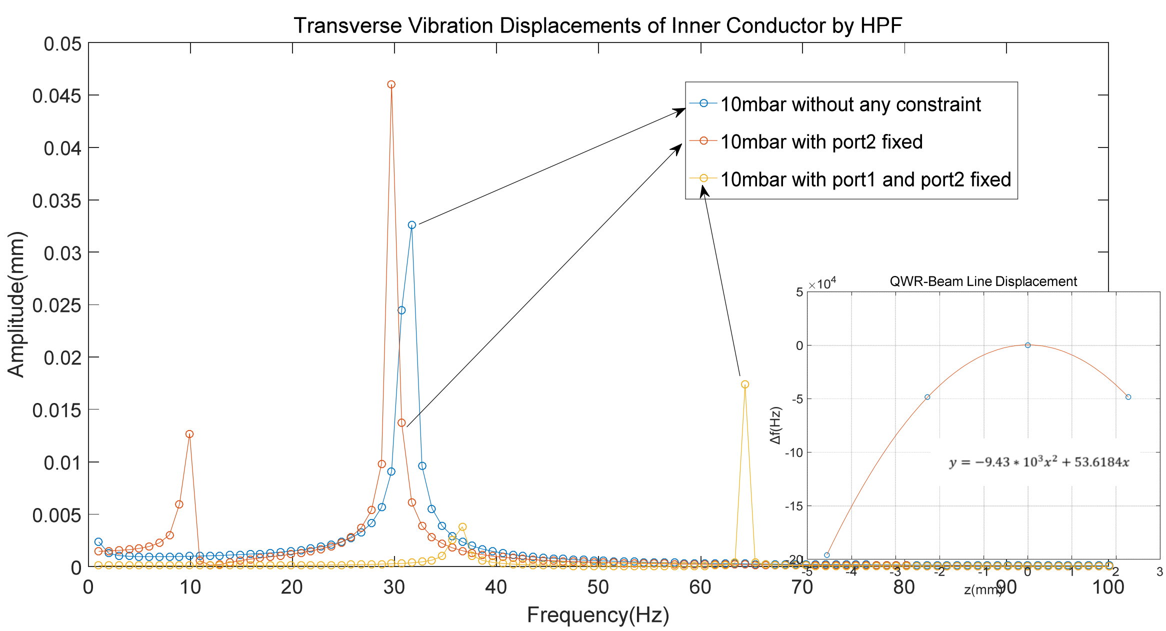

Figure 3: Transverse frequency response of drift tube to HPF.

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the vibration mode will degenerate to 2 modes with relative narrow bandwidth, the values of 2 mechanical resonant frequencies may get larger or smaller than 31 Hz depend on the cavity constraint condition. Thus it is necessary to be careful with possible external low frequencies resonant sources even with a stiffening rib.The frequency shift Δf is a quadric function of the transverse displacement Δz of inner conductor, which is shown in Fig. 3.

MULTIPACTING SIMULATION

For the QWR cavities, multipacting effect is another issue to consider in the cavity design stage. Large number of electrons build a stable resonant process, absorbing RF power so that it becomes impossible to increase the cavity fields by raising the incident power. The electrons collide with the structure walls leading to temperature rise and eventually may cause cavity thermal breakdown [9]. Generally in QWR, the most serious multipacting regions are top shorting plate, power coupler port and beam pipe in certain accelerating gradient. We firstly simulated the MP effect of shorting plate, which was finished in CST Particle Tracking Solver.

A first-order two-points multipactor barrier occured in the region of top shorting plate, the relative MP intensity is above 1 in the accelerating gradient range of 1.8MV/m~2.4MV/m, the number of electrons grows exponentially over time, that represents a high possibility that multipacting effect may occur. To avoid possible multipacting effect, we modified the inner fillet radius of top shorting plate-see Fig. 4 (a), from 30mm to 20mm, then we recalculated the multipacting effect, as we can see in Fig. 4 (b), the relative MP intensity in the calculated accelerating gradient range is below 1. This is a traditional way to lower the possibility of multipacitng effect in the design stage, the effect of the asymmetric shorting plate to the mechanical properties will be further studied. Multipacting on rinse port and power coupler port will also be studied next.

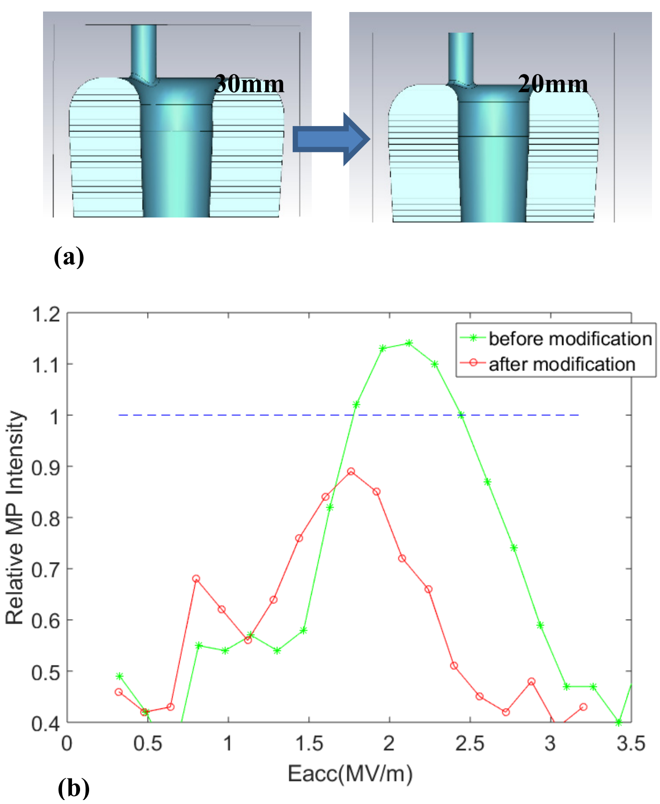

Figure 4: Top shorting plate modification (a) relative MP Intensity before and after modification (b).

CONCLUSION

Peking University has designed an 81.25 MHz QWR cavity for low beta high current ion beams. Simulations and analysis of electromagnetic and mechanical properties were performed in this paper. The coefficient of Lorentz Force Detuning of naked cavity is about -5.296 Hz/(MV/m)^2, a vibration mode differentiation of inner conductor occurred under various ports constraints. For multipacting effect, an asymmetric top shorting plate is adopted to lower the possibility of multipacting.

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