Design of undercuts and dipole stabilizer rods for the CPHS RFQ accelerator*

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Abstract: As part of the design and machining of the RFQ accelerator in the Compact Pulsed Hadron Source (CPHS) project at Tsinghua University, the design process of the undercuts and dipole stabilizer rods is presented in this paper. In particular, the relationship between the inter-vane voltage slope and the local frequency of the undercut section is described quantitatively. With the identification of modes existing in the cavity, the specific parameters are optimized by the SUPERFISH and MAFIA codes. In addition, the water-cooling requirement of the dipole stabilizer rods is briefly discussed.

Key words: RFQ accelerator, undercut, dipole stabilizer rod

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1 Introduction

A four-vane RFQ accelerator is adopted in the Compact Pulsed Hadron Source (CPHS) project at Tsinghua University. With an operating frequency of 325 MHz, one proton beam with a pulse intensity of 50 mA and duty factor of 2.5 % will be accelerated from 50 keV to 3 MeV [1]. The total length of the RFQ cavity is approximately 3 m without coupling cells. On the basis of the whole cavity profile, the design of the undercut and dipole-mode stabilizer rods is necessary in order to approach the designed field distribution of the operating mode and avoid disturbance from the adjacent dipole modes.

By simulation, the first 10 modes in the RFQ cavity are identified, and are found to be either dipole or quadrupole modes, which are all similar to transverse electric-field modes. The existence of dipole modes in the cavity will lead to a decrease in beam quality. Therefore, there should be large frequency intervals between the operating mode TE_{210} and its neighbourhood dipole modes.

For the TE_{210} operating mode, Hz varies twice around the four quadrants and its orientation remains almost unchanged along the z axis. The magnetic lines of the flux circles through the undercuts and the quadrupole electric field assures the transverse stability of the accelerating particles.

For the dipole mode, Hz varies just once angularly. If we use "+" and "−" to indicate the direction of Hz in the four quadrants, the degenerated dipole modes can be written as (+−−+、++−−) or (+0−0、0+0−), as shown in Fig. 1. Generally, the mode in an actual RFQ cavity is approximated as a mixture of the quadrupole modes and dipole modes.

2 The design of the undercuts

The parameters of the undercuts should be optimized so that the inter-vane voltage distribution approaches the designed curve. The design principles of the matching undercut may be demonstrated as Eq. (1) [2]:

$$\frac{1}{2}\left(\frac{c}{2\pi f_0}\right)^2\frac{\partial V_g}{\partial n}(L)=\frac{L}{f_0}(f(L)-f_0)V_g(L), \qquad (1)$$

where f_0 is the resonant frequency, V_g is the inter-vane voltage and $f(L)$ is the local frequency of an undercut segment with length L.

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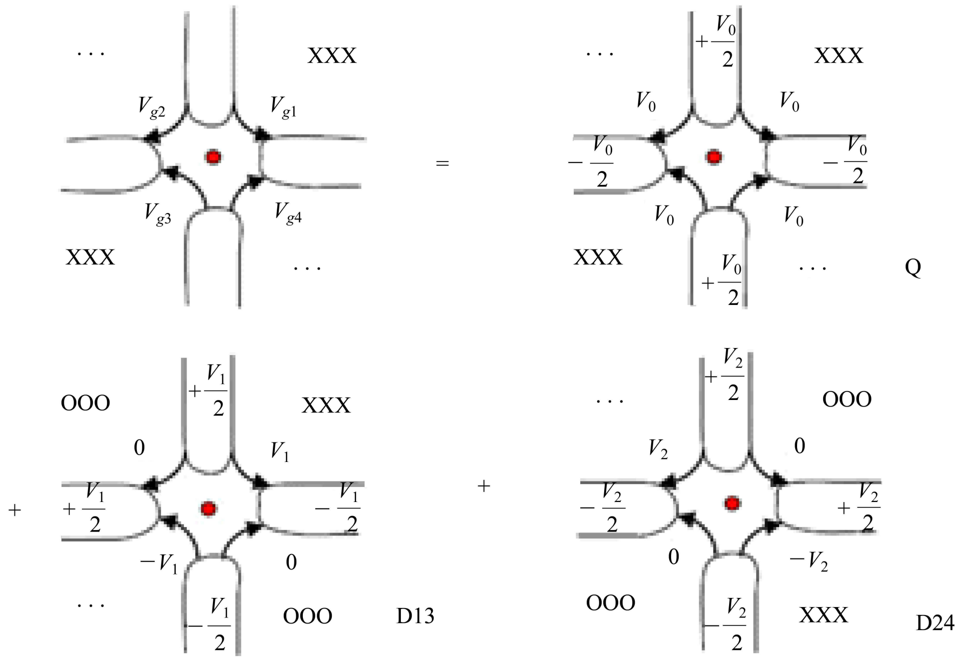

Fig. 1. Field analysis of the operating mode in the actual RFQ cavity.

Proof: assume that there is an undercut section with length $L+\Delta L$. When the magnetic boundary condition is adopted, the resonant frequency is also its local frequency $f(L+\Delta L)$. The vane voltage doesn't change at $z=L+\Delta L$ where no magnetic flux leaks between the adjacent quadrants:

$$V_g'(L+\Delta L)=0. \tag{2}$$

According to the Maxwell wave equation, in the period $z=L\sim L+\Delta L$, the voltage variation along z obeys Eq. (3) [3]. f_c is the cut-off frequency of a cross section:

$$\left[2\frac{f_0-f_c(z)}{f_0}+\left(\frac{c}{2\pi f_0}\right)^2\frac{\partial^2}{\partial z^2}\right]V_g(z)=0. \tag{3}$$

Therefore, the slope of voltage at $z=L$ can be derived from Eq. (2) and Eq. (3), written as Eq. (4):

$$\left[\frac{c}{2\pi f(L+\Delta L)}\right]^2 V_g'(L) -2\frac{f(L+\Delta L)-f_c}{f(L+\Delta L)}V_g(L)\Delta L=0. \tag{4}$$

Eq. (5) can be obtained according to the Slater perturbation theory. $f(L)$ is the local frequency for the undercut segment with length L:

$$f(L+\Delta L)=\frac{f(L)L+f_c\Delta L}{L+\Delta L}. \tag{5}$$

Eq. (6) can be presented with the combination of Eq. (4) and Eq. (5):

$$\frac{1}{2}\left[\frac{c}{2\pi f(L+\Delta L)}\right]^2\frac{\partial V_g}{\partial z}(L) =\frac{L}{f(L+\Delta L)}[f(L)-f(L+\Delta L)]V_g(L). \tag{6}$$

Apparently, Eq. (6) gives the relationship between frequency detuning and voltage slope, as Eq. (1) shows.

When an undercut segment with a certain length is chosen to be calculated, the local frequency would be obtained from the expected resonant frequency and the voltage distribution along z, as shown in Eq. (1). A Mafia model with a 20 cm long undercut segment is established, where the undercut size is predicted to be much smaller in contrast to its whole length. The result shows that the expected local frequencies of the undercut segment at the low energy and high energy ends are 330.47 MHz and 321.63 MHz, respectively. The local frequency is particularly high without undercut near the vane ends. By removing the metal material in the undercut region, the local frequency would be lowered effectively. According to the Slater perturbation theory, the specific shape of the undercut is not very important. A trapezoid-shape-like undercut is adopted for the CPHS RFQ with consideration of its cooling convenience, as shown in Fig. 2.

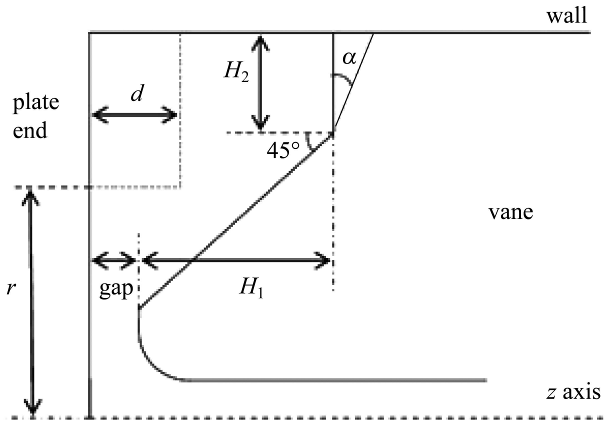

Fig. 2. The undercut parameters.

In our previous work the questionable design procedure was adopted, and thus the voltage distribution didn't achieve our goal in which the voltage curve should be tilted from the low energy end to the high energy end. With more materials cut at the high energy end and some material added at the low energy end, the voltage curve slope seems approximately right in the end, as shown in Fig. 3. In Fig. 3, the voltage is obtained through magnetic field data (the green line) and electric field data (the red line), which are so close to each other that the voltage verification can be measured through the bead pulling method. The undercut parameters are finally applied as Table 1.

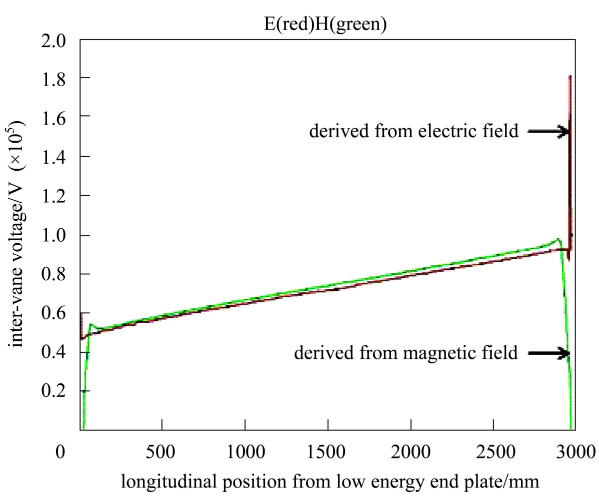

Fig. 3. The voltage distribution along z with the matching undercut.

It shouldn't be forgotten that errors in computer simulation and machining afterwards cannot be avoided. However, the end tuners can raise the local frequency of the undercut in the final tuning. Therefore, the target frequencies given in Table 1 are slightly lower than the expected counterparts.

Table 1. The parameters of the designed undercuts.

end	H_1/mm	H_2/mm	d/gap	r/mm	α/(°)	f/MHz
low	50.3	20	3.5	80	0	330.14
high	39	39	0	80	10	319.97

3 The design of the dipole-mode stabilizer rods

The dipole mode in the RFQ would impose a transverse vectored force on the accelerating particles, causing unnecessary beam loss on the cavity wall. In the CPHS RFQ, dipole-mode stabilizer rods are adopted as a possible easily manufactured solution. With the rods, the dipole-mode frequencies can be shifted, while the quadrupole counterparts are fixed as almost initial. The parameters of the dipole-mode stabilizer rods to be designed include the diameter "D", the central position "r" between the centre of the rods and the beam axis, and the length of the rods "l".

"D" should not be too large, otherwise the operating mode will be fiercely disturbed. It should not be too small either, considering the mechanical strength and convenience of possible water cooling. Generally, 5 to 10 mm is the proper range [4]. For the CPHS RFQ, D=15 mm is finally adopted.

Considering the small impact on the operating mode, the rods should be placed where the energy density of the electric field is equivalent to the energy density of the magnetic field. Due to the symmetry of the cavity, the rods should be placed somewhere in the angular bisector between adjacent vanes. The SUPERFISH code is applied to find the proper "r". A 1/8 cross-section model derived from the structure data of the low energy end is established, as demonstrated in Fig. 4. Without rods, the TE_{210} mode frequency is 323.504 MHz. Only when the rods are inserted with r=5.535 cm, can the operating mode frequency be approximately kept to what Fig. 5 shows. By the same rule, "r" in the high energy end could also be found as 5.554 cm.

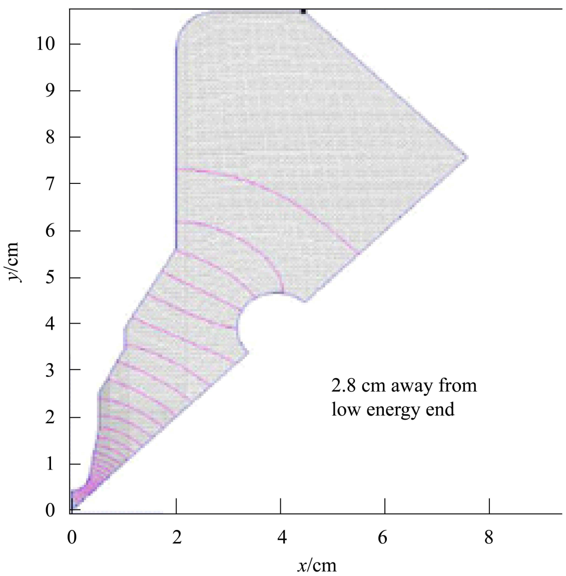

Fig. 4. The SUPERFISH 1/8 model.

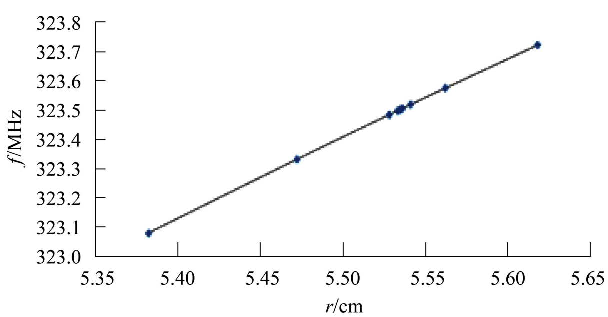

Fig. 5. The "r" sweep curve on the low energy end.

Afterwards, 3D MAFIA code is used to calculate "l". Without the dipole-mode stabilizer rods inserted into the end plate, the frequency difference Δf between the operating mode and the nearest dipole mode is less than 2 MHz. By adjusting "l", a functional relationship between Δf and l can be provided, like parabolic trends. When l=14.7 cm, Δf could be maximal, as Fig. 6 demonstrates.

In theory, the "r" found with the above method would be inappropriate in a 3-D situation because of the longitudinally varied geometry of the undercut. However, the field is relatively weak near the end plate and "l" is much larger than the size of the undercut, so "r" needn't be changed in the 3D simulation. To clarify it, the simulation result is given here. When l=2 cm, the dipole-mode stabilizer will have the greatest influence on the operating mode, but the frequency change is not larger than 0.1 MHz compared with the non-rod situation.

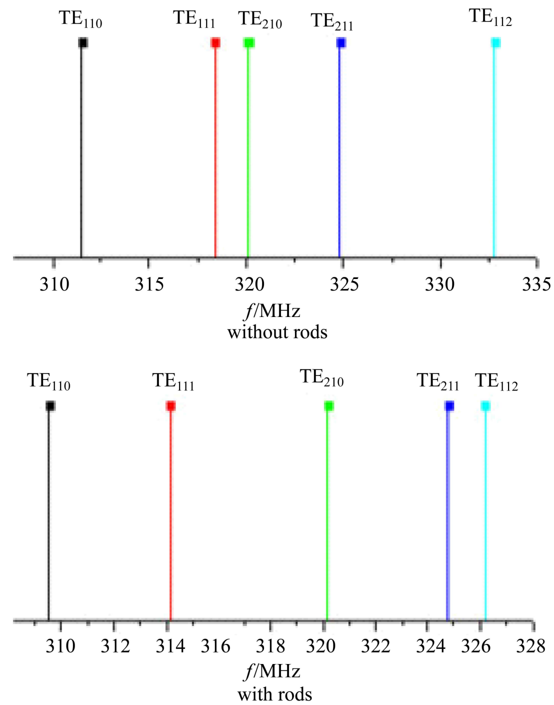

Fig. 6. The spectrum with/without eight rods inserted.

Finally, the thermal analysis on the dipole-mode rod is processed. According to the data output, heat generation density is obtained. This shows that the closer the surface of the rod is to the end plate, the lower the power dissipation is. It is obvious that the centre of the temperature on the rods will be farther away from the end plate as the power loss gradient becomes greater. With a fixed total heat generation on the rods, the farther centre of temperature induces the higher temperature rise on the rods. As a rough estimation, the value of the gradient in the output data is larger than the one in constant distribution and less than the one in linear law. So the range of the highest temperature on the rods can be gained by the results of the above two simplified situations. ΔT is used as the highest temperature rise on the rods relative to the end plate. Through estimation, ΔT on the eight rods would be around 20 ℃, thus the water-cooling system on the rods is unnecessary.

4 Discussion

The design of undercuts and dipole-mode stabilizer rods is done by simulation of the MAFIA and SUPERFISH codes. Numerical errors should be reduced as much as possible, so the grid refinement and convergence analysis can be taken carefully before the final result is given. However, computer resource limits hamper the accuracy and precision of the results. The conclusion about the length of the rods is particularly suspicious since the undercut calculation error already exists. Besides, the length of the rods can be finally adjusted by experimental methods. The theoretical calculation can be taken as a reference.

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