Study of influence of radial matcher section end shape on RFQ cavity frequency*

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Abstract: To investigate the feasibility of using a form cutter to machine the Radial Matcher Section (RMS) of the Radio Frequency Quadrupole (RFQ) for the Accelerator Driven System (ADS) project at Institute of Modern Physics, Chinese Academy of Sciences (IMP, CAS), the influence of RMS end shape on the RFQ cavity frequency is studied. The results indicate that using a form cutter to machine the RMS of an RFQ will indeed influence the cavity frequency. The RMS end shape will give more influence to a shorter RFQ cavity. For the 4.2 m ADS RFQ, the influence is negligible, which means that a form cutter can be used to machine the RMS.

Key words: ADS project, form cutter, radial matcher section, test module

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1 Introduction

A four-vane Radio Frequency Quadrupole (RFQ) accelerator has been designed at the Institute of Modern Physics, the Chinese Academy of Sciences (IMP, CAS) for the Accelerator Driven System (ADS) project, which has been running in China since 2011 [1]. As one of the main components of Injector Ⅱ of the China ADS linac, the RFQ works at a frequency of 162.5 MHz and accelerates the proton beam of 15 mA from 30 keV to 2.1 MeV. The main parameters of the RFQ are listed in Table 1. Fig. 1 shows the mechanical design of one of the four modules of the ADS Injector Ⅱ RFQ, which has 20 tuners and 4 pairs of Pi-rods. The detailed design of the vane-tips and the radial matcher section (RMS) is also displayed in Fig. 1. The vane-tip geometry has a constant transverse radius design with ρ=4.3 mm, which allows machining of the vane-tip with a form cutter and which reduces the risks of variable radius vane cutting and increases the machining efficiency [2].

A test module (as shown in Fig. 2) has been fabricated to check the designed fabrication procedure and to get machining experience. However, we found that the RMS end shape of the vanes of the test module were different from those designed after we had finished machining, which was due to the use of a form cutter. In addition, the frequencies of the fabricated model and the CST (Computer Simulation Technology) model have a

Table 1. Main parameters of ADS Injector Ⅱ RFQ.

ion species	proton
frequency/MHz	162.5
input/output energy/MeV	0.035/2.1
current/mA	15
input emittance (nrms)/(πmm·mrad)	0.3
output trans. emittance (nrms)/(πmm·mrad)	0.31
output long. emittance/(keV·ns)	0.92
$\alpha_{\rm in}/\alpha_{\rm xout}$, $\alpha_{\rm yout}$	1.21/0.36, −0.3
inter-vane voltage/kV	65
$K_{\rm p}$ factor	1.2
minimum aperture/mm	3.2
modulation	1–2.38
synchronous phase/(°)	−90–−22.7
cavity length/cm	420.8
transmission efficiency (%)	99.6

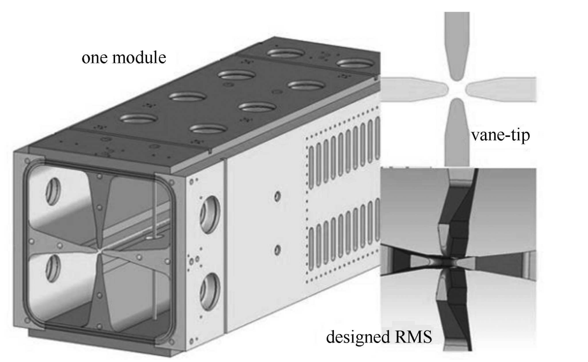

Fig. 1. (color online) Mechanical design of the ADS Injector Ⅱ RFQ.

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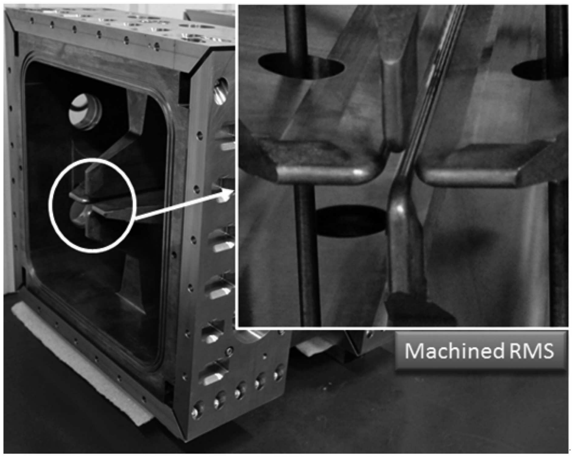

Fig. 2. The test module.

big difference of 165.291 MHz and 164.639 MHz, respectively, when the insertion depth of the tuners is 20 mm.

Usually the end of the RMS of a vane-tip is designed to have a flat surface, but the flatness will be destroyed if a form cutter is used to machine the RMS. Since there is little research on the influence of the RMS end shape on the RFQ cavity performance, studies have been carried out to understand the influence of RMS end shape on cavity frequency and to verify whether or not a form cutter can be used to machine the RMS of the real RFQ.

2 Influence of RMS end shape on cavity frequency

Some investigations have been carried out to figure out how much influence the RMS end shape has on the cavity frequency. Because it is machined by a form cutter, the RMS end will have the same breakout angle as the vane-tips. In Fig. 3, alpha denotes the breakout angle, and its change will alter the shape of the RMS end. The dashed lines in Fig. 3 constitute the RMS profile, which is the same shape as the designed profile (as shown in Fig. 1).

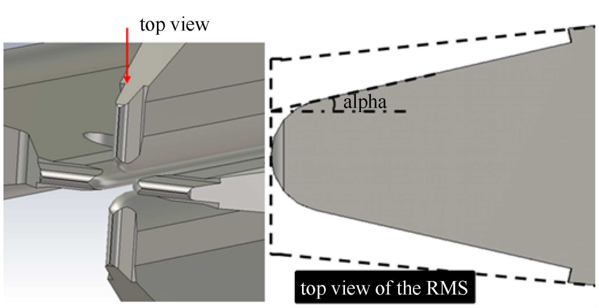

Fig. 3. (color online) The RMS end shape and its breakout angle.

Figure 4 displays the influence of the breakout angle on the frequency of the test module. It shows that a smaller angle will give a bigger cavity frequency.

Two factors cause the cavity frequency change, one is the capacitance between the cavity end plate and the ends of vanes, as well as the coupling capacitance between neighboring vanes, and the other is the inductance of the vanes. Changing the breakout angle of the RMS end will alter the capacitances and the inductance, a small angle leads to small areas that constitute the capacitances and big distance between the areas, accordingly the capacitances are small. The magnetic field is closed around the vanes, a small angle results in short magnetic field path, hence the inductance becomes small. All of the increases or decreases of the capacitances and inductance will produce a decrease or increase in the cavity frequency.

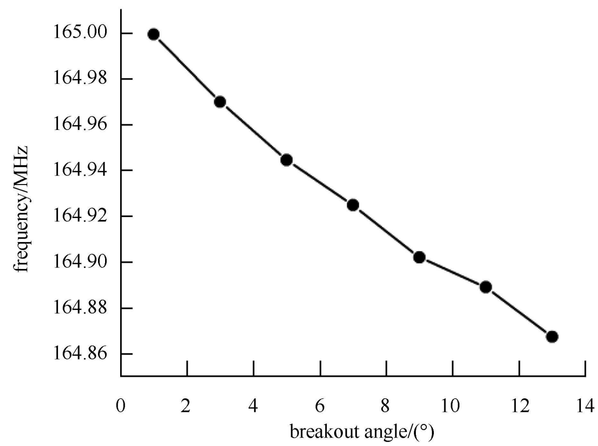

Fig. 4. The cavity frequency vs different breakout angles.

When Alpha is 90°, the RMS has an end shape as the designed one and the cavity frequency is 164.639 MHz. When the breakout angle is 10°, which is the same shape as that of the form cutter, the cavity frequency is 164.940 MHz, and the frequency difference between the test module and CST model is 0.351 MHz, which is not too big and is acceptable.

To know the influence of RMS end shape on the 4.2 meter long RFQ cavity, two full length models were built and simulated by CST code, for which only the end shape is different. The results show that the cavity frequency is 162.4016 MHz when the RMS end shape is flat and the cavity frequency is 162.4351 MHz when the RMS end shape is round. To ensure the simulation accuracy, mesh convergence was carried out and the final accuracy is 0.021%. Taking the simulation accuracy into consideration, the above two frequencies are almost the same, which means that a form cutter can be used to machine the RMS of the 4.2 meter long RFQ, although special treatment is required to make the RMS smooth.

The RMS end shape not only affects the frequency of the four-vane RFQ cavity but also affects that of the four-rod RFQ cavity. Two four-rod RFQ cavity models with a length of 2.5 m built for the SSC-LINAC at IMP [3] were simulated with CST code (as shown in Fig. 5), which are the same except the RMS end shape. The results show that the cavity frequencies are 53.3141 MHz and 53.4197 MHz for the flat RMS end shape and for the RMS end shape with a breakout angle of 10°, respectively.

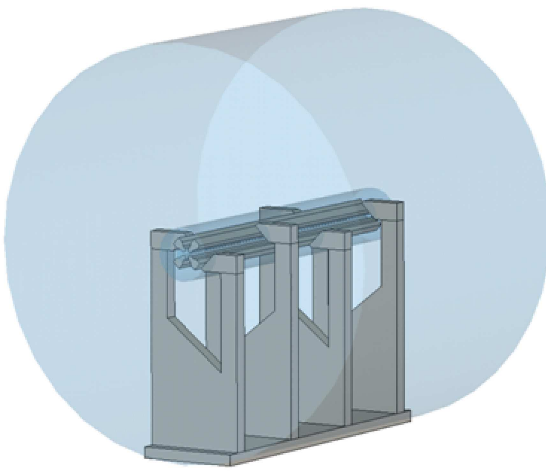

Fig. 5. (color online) The four-rod RFQ cavity built for the SSC-LINAC at IMP.

3 Influence of RMS end shape on field distribution

The influence of RMS end shape on field distribution is studied at the same time, and the results are shown in Fig. 6. It should be noted that the fields are calculated along the curve, which has a coordinate of (12 mm, 12 mm) at the cross section of the cavity and a total energy of 1 J in the cavity. This indicates that all of the field distributions are identical along the cavity length for different breakout angles, except at the RMS region. A small breakout angle leads to a low field at the RMS region, and a big breakout angle brings about a high field. As mentioned in the above section, a small breakout angle generates small capacitances, which produces low local stored electric energy and low field intensity.

The formula of the stored electric and magnetic energy are $U_\theta = \frac{1}{4}V^2C$ and $U_m = \frac{1}{4}\frac{V^2}{\omega^2 L}$, respectively. Where, V is the cavity voltage, C and L are the capacitance and inductance, and ω is the cavity frequency. A small breakout angle means a small inductance; accordingly, the local stored magnetic energy becomes big. This is the reason why the field distributions are still the same for different breakout angles, except at the RMS region, although the total energy is constant.

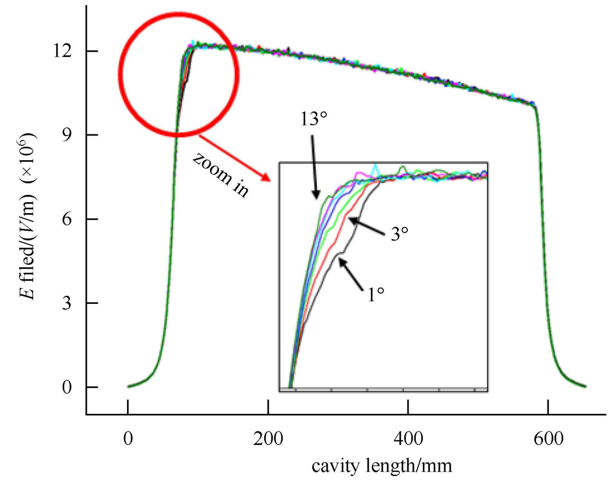

Fig. 6. The field distribution vs different breakout angles.

4 Conclusion

To determine the feasibility of using a form cutter to machine the RMS of an RFQ cavity, some investigations have been carried out. It turns out that the RMS end shape will have an effect on the cavity frequency. In addition, vane tips that are machined with a form cutter that has a smaller breakout angle will give a bigger cavity frequency. That is to say, a form cutter cannot be used to machine the RMS of a short RFQ cavity unless the RMS is designed to be machined with a form cutter at the beginning. At the same time, our results show that the influence of the RMS end shape becomes smaller when the RFQ cavity is longer.

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