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Simulation and experiments of rf tuning of a 201.5 MHz four-rod RFQ cavity *

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Abstract: A four-rod radio frequency quadruple (RFQ) cavity has been built for the Peking University Neutron Imaging Facility (PKUNIFTY). The rf tuning of such a cavity is important to make the field distribution flat and to tune the cavity's resonant frequency to its operating value. Plate tuners are used to tune the RFQ, which have an effect on both the cavity frequency and field distribution. The rf performance of the RFQ and the effect of plate tuners are simulated. Based on the simulation, a code RFQTUNING is designed, which gives a fast way to tune the cavity. With the aid of the code the cavity frequency is tuned to 201.5 MHz and the flatness deviation of the field distribution is reduced to less than 5%.

Key words: four-rod radio frequency quadrple, rf tuning, simulation

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1 Introduction

A 201.5 MHz four-rod radio frequency quadrple (RFQ) has been developed at Peking University for the thermal neutron imaging facility PKUNIFTY [1]. The RFQ has four mini-vanes, which accelerate the injected 50 keV D^+ ions up to 2 MeV [2, 3]. The duty factor of the beam is 10% and the maximum pulse duration is 1 ms. The RFQ's parameter details are listed in Table 1. The neutrons are produced by a D-Be reaction. The 4π fast neutron yield is expected to be 3×10^{12} n/s, and the thermal neutron flux is 5×10^5 n/cm^2/s at the imaging plane [4].

According to the beam dynamics design, the inter-vane voltage between neighboring electrodes along the longitudinal accelerating cells should be kept constant [2], which is important for the injected ions to get an appropriate transverse focus and longitudinal acceleration. If the voltage in some sections does not fit the designed value, it will cause beam loss [5]. In the RFQ cavity the voltage between neighboring electrodes is proportional to the local field, which is easy to measure, so we usually study field distribution rather than voltage distribution. We expected to improve the flatness of the field distribution to a deviation of less than 5%.

Table 1. Designed parameters of the four-rod RFQ.

parameters	value
frequency/MHz	201.5
inter-vane voltage/kV	70
cavity length/mm	2700
cavity diameter/mm	300
maximum modulation	1.89
electrode tip radius /mm	2.73
aperture radius (mean)/mm	3.64
rf dissipation/kW	270

In a four-rod RFQ the electrodes are supported by a number of stems. A cell of the rf structure consists of two adjacent stems with the electrodes and base plate in between. This is illustrated in Fig. 1. To tune the RFQ, both plate tuners and stick tuners are used as shown in Fig. 1. The stick tuners are used for fine frequency tuning, especially for tuning the small frequency shift during RFQ operation. The plate

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tuners inserted between the two stems can be used to tune the local frequency and field, and the RFQ frequency and field distribution can be tuned effectively by inserting plate tuners with a suitable thickness into selected cells.

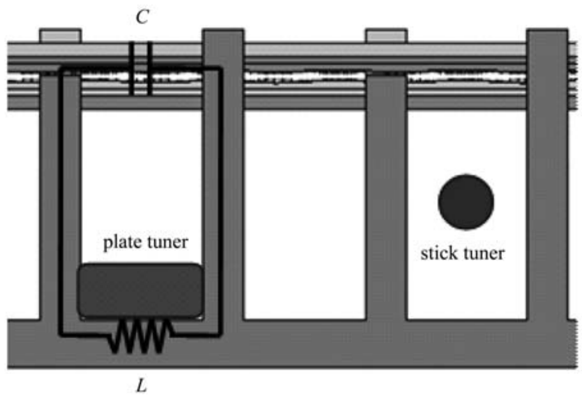

Fig. 1. Schematic structure of the RFQ and the plate and stick tuner.

In this paper we shall mainly discuss tuning with plate tuners. The rf performance of the RFQ with different combinations of plate tuners is studied by the Computer Simulation Technology Microwave Studio (CST MWS) simulation. In order to make rf tuning more efficient, a code RFQTUNING has been developed based on the simulation results, which can give the optimized plate configuration quickly, for example, where the plates should be inserted and what dimensions they are.

2 Method

As shown in Fig. 1, each cell of the cavity is equivalent to a resonant circuit containing a capacitance given by the neighboring electrodes and an inductance loop which consists of the stems and the base plate [5, 6]. If the distributed capacitance and inductance in all the cells are the same, all the cells could have the same resonant frequency and the field distribution along the electrodes would be flat. If such a condition is not satisfactory, the inserted plate tuner can cause the inductance of the resonant circuit to decrease, so the local frequency goes up and the local field goes down.

When the CST MWS is used to simulate a four-rod RFQ cavity with unmodulated electrodes, a rather flat field distribution can usually be obtained, which is just a little uneven at the two terminals due to the end-effect [7, 8]. However, the distributed capacitance and inductance of the RFQ with modulated electrodes is more complicated. The aperture radius of the RFQ changes along the electrodes according to the beam dynamics design. The equivalent distributed capacitance becomes smaller and smaller, as the cell length at the higher energy end becomes longer and longer. So the field distribution along the modulated electrodes is quite different from the unmodulated one. In addition, eight stems of the RFQ cavity are thicker than the others for mechanical and thermal reasons, which makes the situation more complicated. As a result, the field variation of the RFQ is much larger than that of an unmodulated RFQ as showed in Fig. 2.

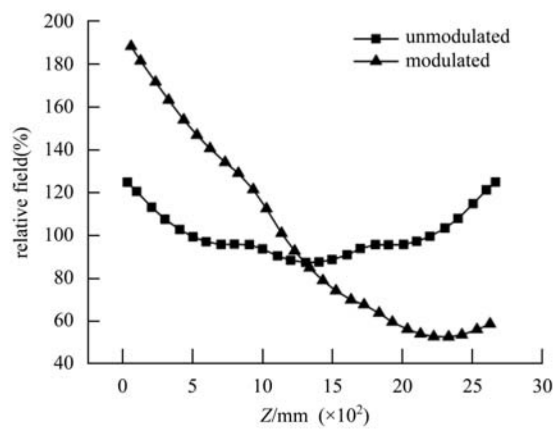

Fig. 2. Field distributions along the electrodes simulated with modulated and unmodulated RFQs respectively.

In fact each plate tuner has an effect on the whole RFQ, and the thicker plate has the greater effect. It is difficult to simply determine the plate configuration, such as how many plates should be used and how thick each plate is. The traditional method is to build a cold model of the RFQ to study its tuning performance. This not only costs more, but also takes a long time. Another method is to use plate tuners in all the cells, and try to tune the RFQ by experiment [9]. The tuning method presented in this paper is a combination of simulation and experiment. The objective of the simulation is to find a plate configuration with as few plate tuners as possible. That is because the plates will increase rf power dissipation in the RFQ cavity and decrease the cavity quality factor [10]. Furthermore, every plate should be water cooled, so more plates mean more water cooling channels, which would complicate the cooling system and increase the probability of damaging the vacuum system. There are a total of 31 local resonant cells in this RFQ cavity, so the possible plate configurations are numerous. To optimize the plate configuration a code RFQTUNING has been developed that can calculate the field distribution of certain configurations, based on the measured data, and then adjust the plate thickness to realize a flat distribution. However the performance of the RFQ cavity also depends on its manufacture and assembly, so experimental tuning is still needed. Actually the process of measuring, simulating and adjusting was carried out in cycles during the experiments until a satisfactory result was obtained.

Electric field measurement is an important step in the above process, which can be performed by a bead-pull method. The measurement bench consists of a bead-pull system, an Agilent 8753ES network analyzer and an industrial PC [11]. Electric-field is indirectly measured by the phase of S_{21}, one of the two-port scattering parameters of the cavity. According to perturbation theory, if the field perturbation is small enough, we can get:

$$\Delta\varphi \propto E^2, \tag{1}$$

where $\Delta\varphi$ is the phase shift of S_{21} caused by perturbation and E is the local field.

In our measurement a dielectric sphere was pulled along the electrodes to perturb the local field. In fact only the relative values of the field are meaningful to the flatness of the field distribution, so we normalize the measured field data and use these relative values in the field distribution study.

3 Simulation and the tuning code

The field distribution and resonant frequency of the studied RFQ with modulated electrodes are simulated by the CST MWS. Plates of different thicknesses in different cells are simulated individually. For instance, the relative field distributions, which are changed by inserting a plate of different thicknesses in the second cell, are shown in Fig. 3(a). After inserting the plate the field of the nearby cells decreases and the field far from the plate increases.

The differences between the field distributions without and with the plate tuner are shown in Fig. 3(b), which indicates that the variation of the field at the same position is approximately linear to the thickness of the plate. Some examples are shown in Fig. 3(c). The variation of the field distribution can be expressed as a line:

$$E_n(h,z) = hf_n(z), \tag{2}$$

where n is the resonant cell number in which the plate tuner is located; h is the thickness of the plate; z is the distance along the electrodes from the entrance; $f_n(z)$ is the slope changing with z. $f_n(z)$ is unknown but we can get the plate's variation of any thickness by a difference method:

$$E_n(h,z) = \frac{E_n(h_2,z)-E_n(h_1,z)}{h_2-h_1}(h-h_1)+E_n(h_1,z), \tag{3}$$

where $E_n(h_1,z)$ and $E_n(h_2,z)$ can be obtained by simulation.

The effect of plate tuners on frequency is also studied, and Fig. 4 shows three instances. The relation of frequency to plate thickness is linear for certain cells. The slopes of these lines are different because of different distributed capacitance and inductance in different cells.

The effect of the plate tuner in every single cell is simulated, and the results are stored in a database. Then the field distribution and resonant frequency for a certain plate configuration can be determined quantitatively. But it is still difficult to find a proper configuration of the plate tuners as the plate added in any cell would influence the whole rf performance. Based on the relationships provided by the above studies, a code is developed to optimize this plate configuration automatically.

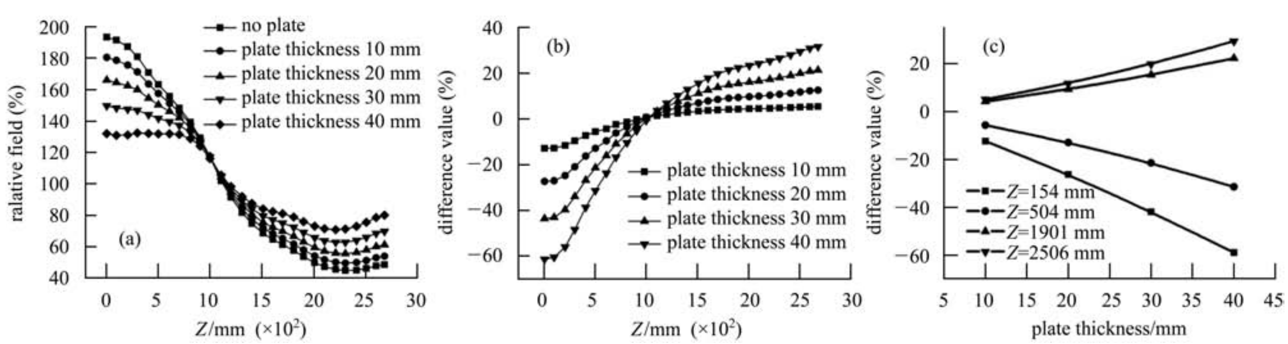

Fig. 3. Field distributions and their differences along the electrodes with plate tuners of different thicknesses in the second cell. (a) Relative field distributions with plate tuners of different thicknesses. (b) Difference values between field distributions without and with plate tuners. (c) Difference values at four longitudinal positions, and the values are linear to the thicknesses of the plate tuners.

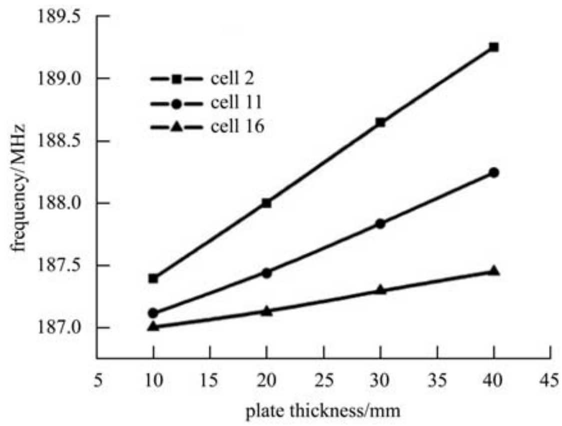

Fig. 4. Frequency effect of the plate tuners in three different cells.

The code starts from the present plate configuration and loads field distribution data. Then it will try to increase the plate thickness around the position with the highest field and to decrease the plate thickness around the position with the lowest field. So a new field distribution is created. The code will check the new distribution and adjust the plate thickness again. If the flatness of the field is good enough, i.e. has a deviation of less than 5%, the code running will be stopped and an optimized plate configuration is given. We can manually change the configuration for fine tuning as well.

4 RFQ tuning and the results

The process of tuning is not simple, because field tuning and frequency tuning interfere with each other. Furthermore, measuring, simulating and adjusting is needed. So it is unrealistic to achieve two tuning targets once and for all; the two tunings are carried out one after the other in cycles.

The field is tuned first, which is much more sophisticated. The untuned field distribution is measured, and then the distribution data are loaded into the RFQTUNING. The code automatically works out an initial plate configuration, which is also manually adjusted to avoid a big frequency difference from 201.5 MHz. The flatness deviation is tuned to be below 5% by the first optimized configuration, and the frequency rises up to 202.8 MHz.

Then we continue to the second step to tune the frequency down to 201.5 MHz. The plates, used for frequency tuning at this step, are discretely chosen to interfere in the field distribution as little as possible. After frequency tuning, we turn back to field tuning. Several cycles later, the frequency is tuned to 201.5 MHz and the deviation of the flatness is below 5%.

The final plate configuration and field distribution are shown in Fig. 5(a) and (b) respectively. In total 17 plates are used, and the flatness deviation is below 5%. It indicates that the measured and simulated field distributions coincide well.

Before the formal tuning process mentioned above, two factors of the bead-pull system are studied and the electrodes are verified and adjusted to the correct position.

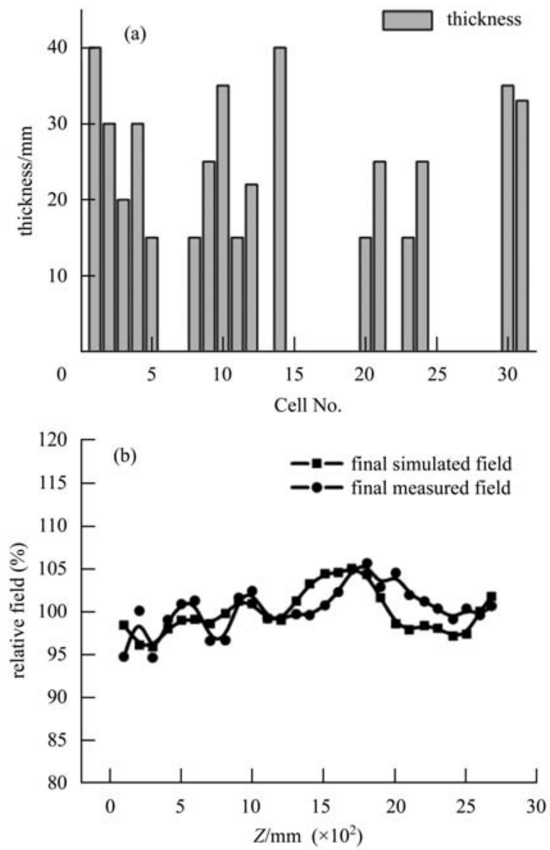

Fig. 5. (a) The final plate configuration. (b) The final measured and simulated field distributions.

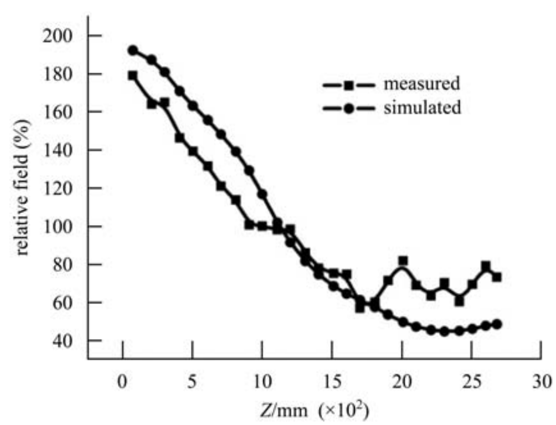

Fig. 6. The measured field distribution before tuning does not coincide with the simulated one because of the dielectric sphere's vibration and inappropriate position.

First, the brackets of bead-pull system are fixed well and the guiding line is tightened to eliminate the dielectric sphere's vibration, which would cause significant signal noise. Second, the sphere located between the electrodes should be at the outer side, because the field at the inner side is not proportional to the voltage as the aperture radius changes along the electrodes. Fig. 6 illustrates that the measured field distribution does not coincide well with the simulated one because of signal noise and the inappropriate position of the sphere.

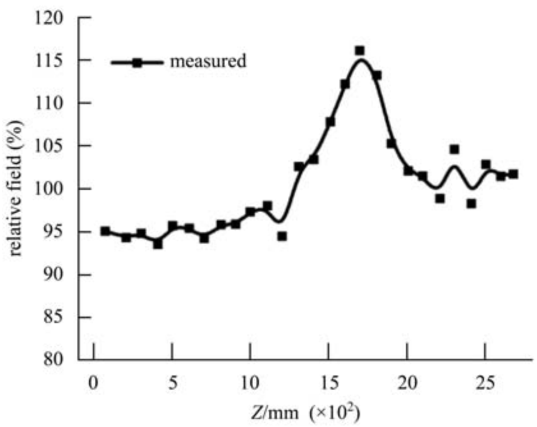

Fig. 7. The measured field distribution after one test tuning. The field values near the longitudinal position of 1750 mm are abnormally high.

Third, verification of the assembly of the electrodes is fundamental in the tuning, particularly because each electrode of the RFQ is assembled with three short electrodes for better cooling and easier manufacture. As rf performance is very sensitive to the electrodes, the field distribution can reflect whether the electrodes are assembled well. The field distribution, shown in Fig. 7, helps us find that the join of the second and the third electrodes is not perfect.

5 Summary

Rf tuning is important for a four-rod RFQ. The rf performance of the RFQ cavity with modulated electrodes has been simulated. A code based on the simulated results was developed to help the tuning process. The code is quite efficient and gives a fast way to tune the RFQ. Only 17 plate tuners are used in the cavity to complete both field and frequency tuning. Four motor driven stick tuners will be used to automatically adjust the fine frequency shift caused by the temperature change during the cavity operation.

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