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Tuning of a One-Meter Four-vane RFQ

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Abstract: In order to get experiences of design, tuning and running of a four-vane RFQ for the China ADS project, a one-meter four-vane RFQ was designed and fabricated. The quadruple frequency of the RFQ was designed to be 162.5 MHz (operating frequency), but the measured frequency after fabrication was 163.7 MHz even without tuners in the cavity. To reduce the frequency the four-wire line model theory was used, and the endplates were redesigned. Dipole mode stabilizer rods were employed to expand the span of the quadruple frequency and the adjacent dipole frequency. As a result, the quadruple frequency was altered to the operating frequency without rippling voltage distribution along the RFQ severely. Meanwhile, the Q value was reduced by 1%, which means more RF power was required to be fed into the RFQ. The dipole mode stabilizer rods were cooled by water to make the RFQ work stably.

Key words: quadruple frequency; dipole frequency; dipole-mode stabilizer rods; end-plate

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1 Introduction

The China ADS (Accelerator Driven Subcritical system) project is established to address nuclear waste processing for nuclear power plants in China. Linear accelerators are used to meet the high energy requirement of the project. To meet the requirements of stability and reliability of the project two linear injectors are used in the low energy section, each of them accelerates proton to 10 MeV[1−2]. All the two injectors use four-vane RFQs as the main accelerators in the normal conducting section, therefore, to get experiences of design, tuning and running of a four-vane RFQ, a one-meter four-vane RFQ was designed at the Institute of Modern Physics, Chinese Academy of Sciences (IMP, CAS). Working at 162.5 MHz the RFQ accelerated proton from 0.35 MeV to 0.6 MeV. The designed voltage was 68 kV and the unloaded Q value was 11 000.

The one-meter RFQ (as shown in Fig. 1) was manufactured and assembled in Shanghai. It had 11 cylinder tuners of diameter of 90 mm, whose depth inside the RFQ cavity could vary from 0 mm to 40 mm and which could tune the cavity frequency theoretically at the range of 161.6 MHz to 163.4 MHz.

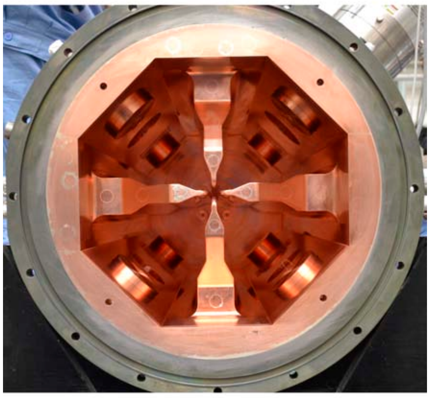

Fig. 1 (color online) Internal view of the one-meter four-vane RFQ.

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Bead pulling method was applied to measure the electric field between the vanes along the RFQ. The measuring system consisted of a dielectric thread, Agilent E5061B Vector Network Analyzer, a system of pulleys, a dielectric spherical bead and a stepping motor which was controlled by a Zolxi SC300-2A controller. Measurement results showed the cavity frequency (quadruple frequency) was 163.7 MHz even without tuners in the cavity, which was higher than the designed frequency. To reduce the cavity frequency some measures were taken and they will be introduced in the following.

2　The end-plates of the RFQ

The original design of the end-plates had flat inner surfaces. It is possible to reduce the quadruple frequency by redesigning the end-plates. The End-Cells of a four-vane RFQ can be modeled as an inductance and a capacitance in parallel connection[3]. The inductance is increased by increasing the distance between the end-plates and vane tips, which reduces the frequency of the End-cells. As the local frequency goes down at the both ends, the quadruple frequency and dipole frequency decrease[4]. The new end-plates were something like a big round flat plate which was dug in the shape of big annular cylinder. Outer diameter of the big cylinder was 379 mm. A small cylinder whose diameter was 130 mm was kept in the center of the end-plates to keep the gap between the end-plates and vanes unchanged, so the beam dynamics of the RFQ wasn't changed. It was found that the quadruple frequency and the dipole frequency decreased by increasing the height of the small cylinder, and the dipole frequency dropped more sharp than quadruple frequency, as shown in Fig. 2. The dipole frequency was higher than the quadruple frequency by more than 5 MHz in the original design, however, after modification of the end plates the dipole frequency got closer to the quadruple frequency which led to the electric fields between the vanes more sensitive to the errors caused by fabrication and assembly, and made the field more asymmetrically. The case had been verified by the low power test, and it can also be demonstrated by the four-wire line model theory[5],

$$U_{\mathrm{di}}(z)=\sum_{n=0}^{\infty}\frac{f_0^2}{4\left(f_{\mathrm{dn}}^2-f_0^2\right)}\frac{2}{l}\int_0^l\cos\left(\frac{n\pi z}{l}\right)\times\left(\frac{\delta C}{C}+\frac{\delta L}{L}\right)\mathrm{d}z\cos\left(\frac{n\pi z}{l}\right)\ ,\quad i=1,\ 2$$

$$U_{\mathrm{d1}}=\frac{V_1-V_3}{2\sqrt{2}\left(V_1+V_2+V_3+V_4\right)}\ ,$$

$$U_{\mathrm{d2}}=\frac{V_2-V_4}{2\sqrt{2}\left(V_1+V_2+V_3+V_4\right)}\ ,\qquad(1)$$

where U_{di} is the dipole term of voltage between vanes. V_1, V_2, V_3 and V_4 are the intervene voltage. f_0 is quadruple frequency, and f_{dn} is a series of dipole frequency. l is the length of RFQ. C and L represent the capacitance and inductance of the ideal RFQ respectively. δC and δL are the error capacitance and error inductance from the ideal one respectively. It can be derived from formula (1) that, the closer the dipole frequency to the quadruple frequency the bigger the dipole voltage, which means a more serious asymmetry of the electric field and a big beam loss in the cavity.

At the end the height of the small cylinder of the entrance end-plate was chosen to be 37.11 mm, and the height of the small cylinder of the exit end-plate was 35.30 mm. In this case, the quadruple frequency was 162.636 2 MHz, and the dipole frequency was 163.474 6 MHz. Dipole mode stabilizer rods were introduced to enhance the frequency separation of the quadruple mode and dipole mode.

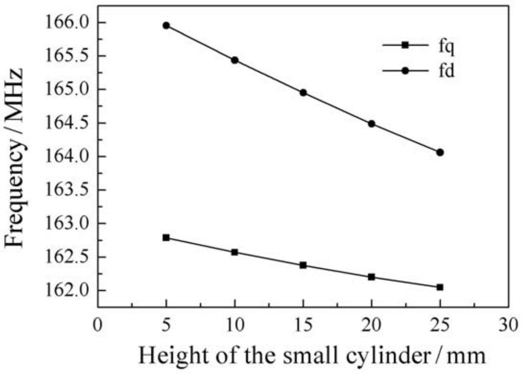

Fig. 2　Influence of the height of the small cylinder on the cavity frequencies.
fq denotes the quadruple frequency, and fd denotes the dipole frequency.

3 The dipole mode stabilizer rods

The dipole mode stabilizer rods are usually used to shift the dipole frequency away from the quadruple frequency[6], but here they would be used to reduce the quadruple frequency, too. To keep the RFQ symmetry, the angle between the symmetric rods line and horizontal vanes is set to 45°[7]. CST MWS was used to determine the geometric parameters of the dipole mode stabilizer rods, including diameter of the rods “D”, radial position “r” and length “lr”. And Fig. 3 shows the results calculated by CST MWS. It shows the cavity frequencies have been increased when increasing the rods length in the magnetic zone, and the cavity frequencies have been decreased when increasing the rods length in the electric zone. The rods act in different ways in the electric zone and magnetic zone. In the four-wire lines model, scale of the cavity capacitance is a function of distance between the vanes[8]. In the electric zone near the beam axis, the dipole-mode stabilizer rods act like reducing the distance between the vanes of the RFQ, and the capacitance in both ends are increased by the rods[9]. Hence, the cavity frequencies decrease by increasing the length and the diameter of the rods. In the magnetic zone far away from the beam axis, the dipole mode stabilizer rods remove the inductance in the ends of RFQ, therefore, the quadruple frequency and dipole frequency increase by increasing the length and diameter of the rods.

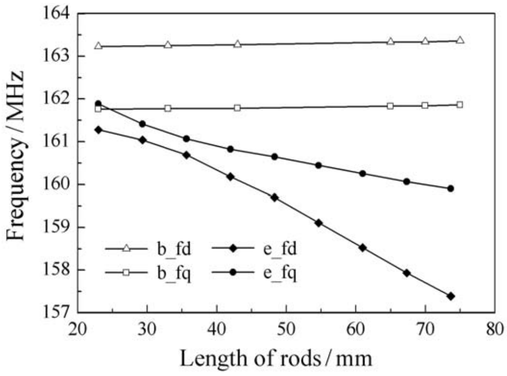

Fig. 3 Influence of the length of dipole mode stabilizer rods on cavity frequencies.
b_fd and b_fq are the frequencies of dipole mode and quadruple mode respectively when the diameter and radial position of the rods are 30 mm and 90 mm respectively in the magnetic zone. e_fd and e_fq are the frequencies of dipole mode and quadruple mode when the diameter and radial position of the rods are 30 mm and 34 mm respectively in the electric zone.

The capacitance and inductance changed by the rods are ΔC and ΔL respectively, which can be regarded as a perturbation of an ideal RFQ. ΔC and ΔL are function of radial position of the rods ‘r’ and diameter of the rods ‘D’. The relationship between the cavity frequency shift Δf and ΔC, ΔL are shown by formula (2), which shows a linear correlation between the length of the rods and the cavity frequencies and which had been confirmed by the low power test, as shown in Fig. 4.

$$\frac{\Delta f}{f_0} = -\frac{l_r}{l}\frac{\Delta L}{L} - \frac{l_r}{l}\frac{\Delta C}{C} \ . \tag{2}$$

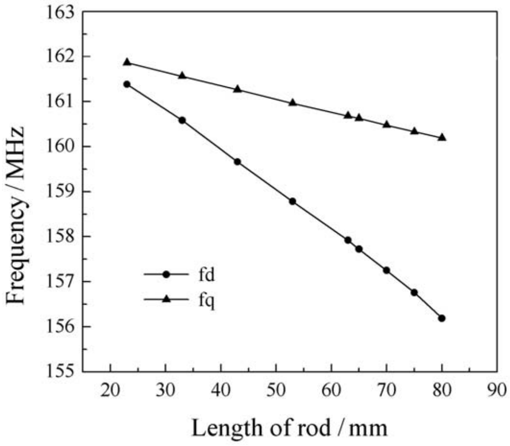

Fig. 4 Cavity frequencies with different rods lengths. fd is the dipole frequency, and fq is the quadruple frequency.

The geometric parameters of the rods were chosen to be $D = 30$ mm, $l_r = 65$ mm, $r = 48.08$ mm. And Fig. 5 shows the rods mounted on the new end-plates. The quadruple frequency was reduced to 160.625 MHz and the dipole frequency was 157.45 MHz with the new end-plates. And then the 11 tuners were used to change the quadruple frequency to 162.5 MHz. Combining the dipole mode stabilizer rods and the new end-plates, the quadruple frequency was finally reduced to the designed frequency. None of them could reduce the quadruple frequency to the designed value alone without getting the dipole frequency close to the quadruple frequency.

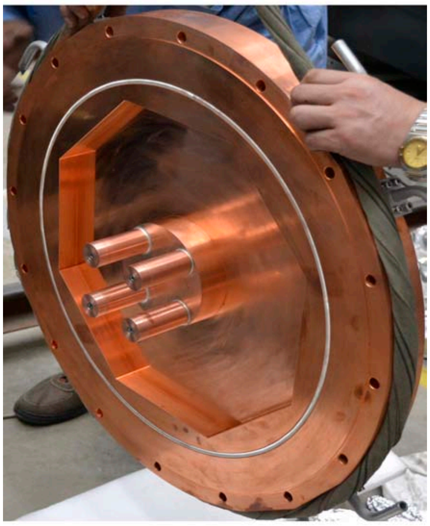

Fig. 5 (color online) Dipole mode stabilizer rods and the new end-plate.

4 Low power test of the RFQ

The dipole mode stabilizer rods mounted in the electric field area brought extra capacitance in both ends of the RFQ. Therefore, the local frequency in both ends of the RFQ was lower than the one in other places of the cavity, which made the inter-vane voltage in the middle of the RFQ lower than that in both ends of the RFQ. Fig. 6 shows the voltage distribution affected by the dipole mode stabilizer rods while the voltage distribution is flat if there is no rods. It also indicates the results calculated by the CST MWS and the four-wire line model agree well with each other.

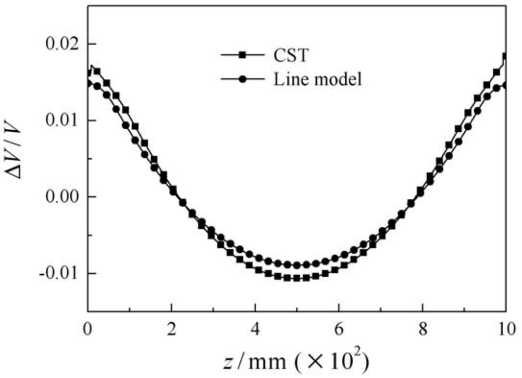

Fig. 6 Inter-vane voltage distribution disturbed by the rods.
"CST" means the result calculate by CST MWS, and "Line model" means the result calculated by four-wire line model.

Bead pulling method was employed to measure the electric field in the condition of 23 ℃. It showed the field of the RFQ at the entrance was 8% higher than the average field. Because the local field strength is a function of local frequency[10], four tuners at the entrance of the RFQ were inserted into the quadrants by 40 mm to tune the local frequency, and three tuners in middle of the RFQ were inserted into quadrants by 3 mm. Three of the four tuners near to the exit of the RFQ were inserted into quadrants by 4 mm, and the rest one was flush with the RFQ inner surface. Fig. 7 displays the inter-vane voltage distributions along the RFQ before and after tuning. It shows the voltage distribution was improved from ±5% to ±2.8% after tuning, and the results of CST MWS simulation, the four-wire line model and the low power test agreed very well with each other.

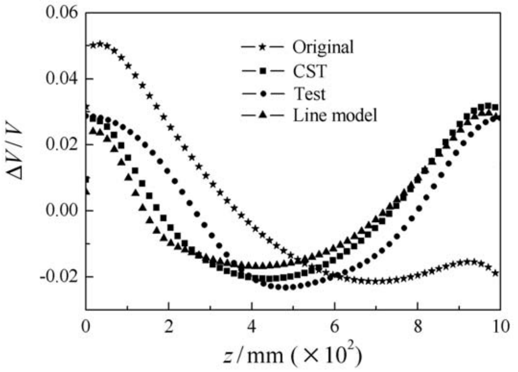

Fig. 7 Inter-vane voltage distribution with and without tuners, the new end plates and rods.
"Original" shows the inter-vane voltage distribution calculated by CST MWS when the cavity had no tuners, dipole mode stabilizer rods and with old end plates. "CST" shows the voltage distribution calculated by CST MWS with tuners, the new end plates and rods. "Test" shows the voltage distribution derived from bead pull perturbation in the low power test with tuners, the new end plates and rods "Line model" shows the inter-vane voltage distribution calculate by the line model with tuners, the new end plates and rods.

5 Conclusion and outlook

A one-meter four-vane RFQ was designed and built at IMP to get experiences of design, tuning and running of a four-vane RFQ. The first low power test showed the cavity frequency was much higher than the designed value. To reduce the cavity frequency the endplates of the cavity were redesigned and dipole mode stabilizer rods were adopted. Finally the quadruple frequency reached the designed one and the frequency difference between the quadruple mode and dipole mode was big enough to make the RFQ work stably. The voltage distribution was within ±2.8% after tuning by the tuners.

The measures taken to reduce the cavity frequency and to expand the span of the quadruple frequency and the dipole frequency can be applied to other four-vane RFQs if it has the frequency problem. But the drawback of the measures is that the dipole mode stabilizer rods have to be cooled by water. Therefore, precise RF calculation of the cavity is the best way to avoid modification to the cavity.

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一米长四翼型RFQ调谐研究

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摘要： 为获取ADS工程中四翼型RFQ加速器在设计、调谐和运行等方面的经验，设计和建造了一台一米长四翼型RFQ加速器。该RFQ的设计频率为162.5 MHz，但是测量结果显示即使没有调谐器时，腔体的频率也为163.7 MHz。为降低腔体频率，使用四线模型理论进行了分析并重新设计了腔体的端板。使用了二极模稳定杆来加大四极频率与相邻二极频率的间隔。最终测量结果显示，在腔体电压分布没有大的波动的情况下腔体频率达到了设计频率。同时，腔体Q值降低了1%，这就要求需要更多的功率注入腔体。使用水对二极模稳定杆进行了冷却，以便腔体能够稳定工作。

关键词： 四极频率；二极频率；二极模稳定杆；端板

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