Layout and High Power Test of a 26 MHz Spiral RFQ*

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Abstract

A flexible spiral RFQ with a tank diameter of 50 cm has been built at Peking University. The quadrupole pole tips can be changed and cooled with water. The frequency can be adjusted by movable short circuit bars. The designed voltage of 80 keV between electrodes has been achieved at rf power of 45 kW with duty factor of 1/6. The RFQ is designed to accelerate N^+ ions to 300 keV. Beam dynamics calculation has been performed and the influnce of pole tip geometry with two dimensional and 4 rod profiles has been investigated. The results of high power test and calculations are presented.

Introduction

The radio frequency quadrupole (RFQ) principle was proposed by Kapchinskiy and Teplyakov in 1970 [1] and successfully tested with a 4 vane cavity in 1980 at LANL. Since then the RFQs have been worldwide developed due to its outstanding features [2,3]. Among them, the 4 rod RFQ has been developed at Frankfurt and becoming popular in these years as well.

With increasing interest in the use of heavy ions, e.g. for ion implantation and inertial fusion, heavy ion RFQs have been developed. Due to the low charge-to-mass ratio and low velocity of heavy ions, such RFQs must operate at low frequency to keep the high current capability. For 4 rod RFQ, low frequency can be achieved by raising the length of support stems, for example with spiral stems as at Frankfurt [4] and LANL [5].

On the bases of investigation of the conventional split ring resonator, an integral split ring or spiral resonator has been developed at Peking University [6]. Instead of drift tubes in this integral structure, quadrupole electrodes, either 4 rods or small 4 vanes, can be excited to provide the quadrupole field. To investigate the performance of this RFQ structure, including the possibility of adjustable frequency, a series of measurement on half and full scale models together with theoretical analysis have been carried out. The results of model measurements show that this RFQ resonator structure is suitable to operate at low frequency and adjustment of frequency is possible. Then a 26 MHz RFQ resonator cavity to accelerate N^+ ions to 300 keV has been designed and constructed [7,8]. Now the high power test has been conducted and beam tests are prepared. Both will be discussed in detail as follows.

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RFQ Resonator Structure and Properties

The parameters of 26 MHz RFQ are listed in table 1 and resonator structure is shown in Fig.1.

Table 1 Principal Parameters of 26 MHz RFQ

f	MHz	26.0
q/M		≥ 1/14
W_{in}	keV/u	2.5
W_f	keV/u	21.4
D (Tank)	cm	50
L (Tank)	cm	90
V_Q	kV	80
ρ	kΩ * m	204
Q		1300

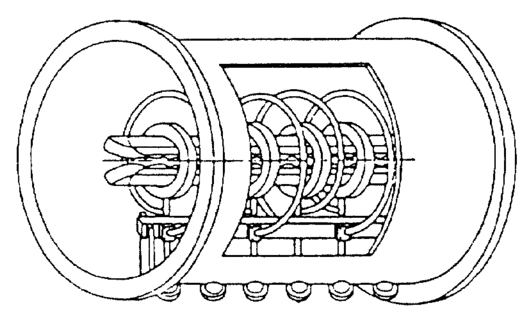

Fig. 1 Schematic drawing of 26 MHz RFQ

The rf structure consists of a base bar, a number of pairs of right-wound and left-wound spiral arms and supporting rings, and 4 rod quadrupole electrodes. They are all made of copper and form an integral structure. For flexibility, quadrupole electrodes fixing on the supporting ring, spiral arms fixing on the base bar, and rf structure fixing in the tank are all by screws, not by soldering or brazing. Therefore, the rf structure can be assembled and aligned outside the tank, then moved in. If necessary, the electrodes and even rf structure can be changed. To reach duty factors as high as 15-25%, the cooling water is designed to flow through spiral pipes, supporting ring and quadrupole electrodes. The outer diameter and thickness of spiral pipes are 30 mm and 1.5mm, respectively. This is strong enough for sufficient mechanical rigidity. The frequency of this rf structure can be changed through moving a short circuit bar between supporting ring and spiral arm to adjust the effective length of spirals as shown in Fig.2.

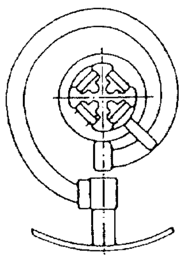

Fig. 2 The RFQ with a short circuit bar

From rf point of view, the spiral arms of rf structure correspond to coupled resonant lines and 4 quadrupole electrodes correspond to two coupled resonant lines. Therefore the rf performance, such as rf mode frequencies and voltages, shunt impedance and Q-value, etc, can be well calculated and explained by means of a lumped equivalent circuit model, which is discussed in a separate paper [9].

High Power Test

The layout of high power test is shown in Fig. 3. The rf amplifier XFD-X5 can deliver cw power of 30 kW or pulse power of 50 kW. The rf power is fed through a water cooled loop. A series of measurements has been conducted to study the influences of loop area and direction, and distribution capacitance of the loop on the input impedance. To compensate the inductance of input impedance, a distribution capacitance has been added into a section of the rf feeder. Then impedance matching has been achieved. During the high power test, the ratio of standing wave is always better than 1.2. The amplitude of electric field in RFQ cavity is stabilized by an electric circuit. The voltage between quadrupole electrodes are determined by the corresponding Röntgen spectrum,

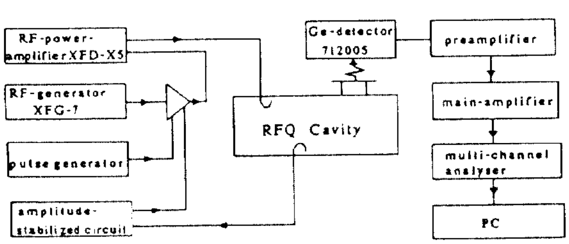

Fig. 3 Layout of high power test

which is produced by the electrons' striking on the electrodes. The maximum energy of Röntgen spectrum corresponds to the voltage between electrodes. The energy of spectrum can be calibrated by the characteristic γ rays of proper isotopes [10]. In the high power test, the γ ray energy of 59.54 keV of Am241 and of 121.78 keV of Eu152 are used to calibrate the maximum energy of Röntgen spectrum. As an example, Fig.4 shows the Röntgen spectrum at rf power of 45 kW. Through linear extrapolation, the calibrated maximum rf voltage is 82.3 kV.

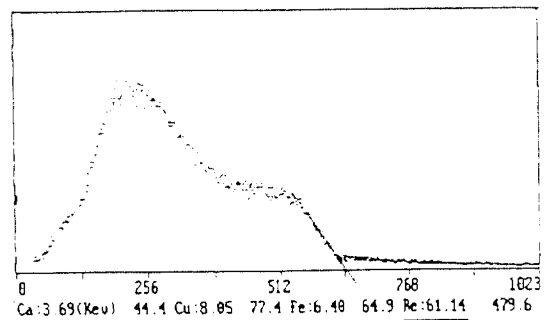

Fig. 4 Röntgen ray spectrum with energy calibration

Table 2 Results of high power test with duty factor 1/6

P_{in}(kW)	19.66	24.62	29.70	39.57	44.36
V_Q(kV)	62.3	66.9	71.6	78.5	81.7
f (MHz)	25.739	25.737	25.733	25.732	25.728
$T_{Wat.}$(^{0}C)	16.5	18.0	19.0	22.0	23.0
ρ (kΩ•m)	168	155	147	132	128

In the high power tests, unmodulated quadrupole electrodes are used. When the vacuum of the tank reaches 10^{-6} torr, rf power starts to be fed in. After rf conditioning, rf power can be easily fed in. Table 2 summarizes some results of high power test with duty factor of 1/6. It shows that the design voltage of 80 kV can be reached at rf power of about 45 kW. At the high power level, the RFQ operates stably. This is also shown by the very small frequency shift in the third row of the table. The water cooling system operates without problems. Compared with the input water temperature of 11°C, the increase of cooling water temperature (row 4) is small, i.e. the cooling system is very efficient. The specific shunt impedance ρ is reduced, as rf power raised. If the capacitive load of the quadrupole electrodes is reduced, the shunt impedance of the RFQ will be improved. In addition, two tests have been specially carried out. One is at high power level of 40 kW with duty factor of 1/6 for 8 hours continuously. Another is at rf power level of 35 kW, but duty factor was raised to 1/4. The corresponding frequency and temperature increase of cooling water are 25.734MHz and 12 °C, resp.. In these two tests, all the electric field stability, vacuum and water cooling system are still quite normal. Therefore, it can be concluded that the design voltage of 80 kV can be stably achieved.

Particle Dynamics Calculation

To prepare beam test, the dynamics calculations have been performed. Fig.5 shows the design parameters for the 26 MHz RFQ [11,12]. To reach a high energy gain in the RFQ (factor 9), the raise in accelerating parameters φ_s and m was made very steep, giving less regard to energy spread and emittance growth at the output. To analyze the influences of quadrupole electrodes with two dimensional profile and 4 rod profile on beam dynamics, the electric fields of these two kind of electrodes has been expanded in multipole and harmonic fields, and compared with ideal two term potential field. Based on the expansion, the dynamics performance has been

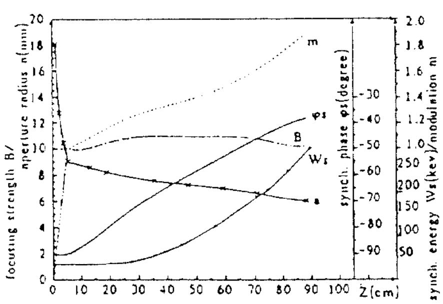

Fig 5. Dynamics parameters of 26 MHz RFQ along electrode

calculated. As an example, Fig.6 demonstrates the calculated transverse and longitudinal phase advances σ_{ot} and σ_{ol} along the RFQ for the electrodes with two dimensional, 4 rod and ideal profiles [11]. From Fig.6, it is clear that for σ_{ol} the two dimensional profile's is some low, but for σ_{ot} the 4 rod profile's is some low. With the same input data, table 3 lists two group of calculated results for two dimensional and ideal profiles, resp.. It shows that the transmission efficiency corresponding to two dimensional profile is a little bit lower than the one corresponding to ideal profile. However, the electrodes with two dimensional profile can be machined easier and have some big transverse section to strengthen mechanical rigidity and to make a bore for cooling water. Therefore, it has been chosen for the first beam test and its schematic drawing is shown in Fig.7.

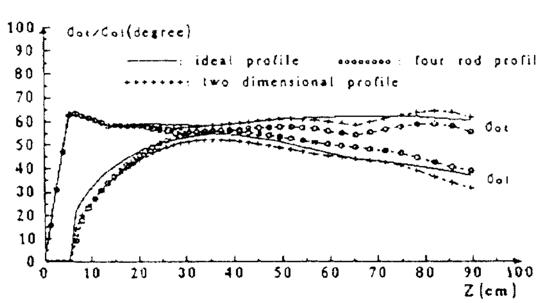

Fig. 6 Phase advances for electrodes with different profiles

Table 3 Results of dynamics calculations for two electrodes with ideal (A) and two dimensional profiles (B).

		α	β mm/mr.	ε π mm.mr.	I mA	ΔW/Ws %
input	x	2.200	0.103	0.232	10.00	0
	y	2.200	0.103	0.232		
output A	x	1.891	0.111	0.934	9.31	-12.00
	y	-1.170	0.0594	0.986		-12.00
output B	x	2.293	0.132	0.829	9.06	-16.70
	y	-1.671	0.0856	0.799		-6.67

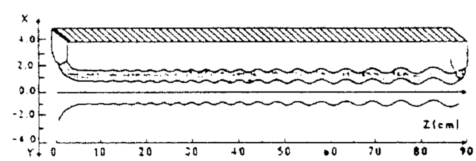

Fig. 7 Scheme of designed electrodes

Conclusions

In the high power test, the design voltage of 80 kV has been achieved at rf power of 45 kW with duty factor of 1/6. Also the high power test with duty factor of 1/4 and high power test operating continuously for 8 hours have been conducted stably. During the test, the water cooling and vacuum systems are quite normal. Therefor, the flexible rf structure will be used to perform beam test. The dynamics calculation shows that the quadrupole electrodes with two dimensional profile seems suitably to be used in the 26 MHz RFQ. Now the beam test is being prepared.

Acknowledgements

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