INVESTIGATION OF THE INTEGRAL SPLITRING RFQ STRUCTURE*

Chen Chia-Erh
Institut of Heavy Ion Physics, Peking University, 100871, Beijing, P.R. China
Fang Jia-Xun, Li Weiguo
Department of Technical Physics, Peking University, 100871, Beijing, P.R. China
A. Schempp
Institut für Angewandte Physik, J.W.Goethe Universität, D-6000 Frankfurt, FRG

Abstract

A 4-Rod RFQ Structure based on the integral splitring and spiral resonators is being studied. A series of full scale model tests and theoretical analysis shows that the resonator suits very well to operate at low frequency for the acceleration of heavy ions with high efficiency, moderate size, good rigidity and adjustable frequency. The features of the structure, rf properties, as well as beam dynamic calculations of a prototype RFQ at 26 MHz for N^+ are presented.

Introduction

The radio frequency quadrupole (RFQ) principle was proposed by Kapchinskiy and Teplyakov in 1970[1] and successfully tested with a four vane cavity in 1980 at LANL[2]. Since then the RFQ has been developed worldwide due to its outstanding features[3]. Now 4-Vane RFQs are commonly used to accelerate light ions.

With the increasing interest in the use of heavy ions, e.g. for ion implantation and inertial fusion, the heavy ion RFQ has been developed. Due to the low charge-to-mass-ratio and low velocity of heavy ions, the heavy ion RFQ must operate at low frequencies to keep the high current capability. But the 4-Vane RFQ is not suitable to accelerate heavy ions below the frequency of approximately 100 MHz, because the diameter of the resonator cavity is inversely proportional to its operating frequency. For example, the diameter of a cavity of a 26 MHz four vane RFQ is over 2.5 meters. However, there are two new types of RFQs, which are suitable to accelerate heavy ions, namely the 4-Rod RFQ (or $\lambda/2$-RFQ) developed at the University of Frankfurt[4] and the Split-Coaxial RFQ at GSI[5].

The 4-Rod RFQ consists of a row of supporting stems and the supported four rod electrodes, which can be excited to provide the quadrupole field. According to making the supporting stems short or long, the 4-Rod RFQ can be easily made to operate at high or low frequency. A 4-Rod RFQ with straight stems at a frequency of 202 MHz has successfully accelerated a 35 mA H^- beam at DESY[6]. Fig. 1 shows a scheme of this structure. The operating frequency of the 4-Rod RFQ can be reduced, if the straight stems are substituted with longer conductors. Examples are the spiral 4-Rod RFQ investigated at Frankfurt[7,8] and LANL[9]. Compared to 4-Vane structures the resonator of the 4-Rod RFQ is not only easily manufactured, but it is also possible to adjust the frequency for the variation of the ion energy e.g. for ion implantation[10,11].

Based on the investigation of the conventional splitring resonator, an integral splitring and spiral resonator has been developed at Peking University[12]. Instead of drift tubes in this integral structure quadrupole electrodes - either four rods or small vanes[4] - can be excited to provide the quadrupole field.

To investigate the properties of this RFQ structure including the possibility of adjustable resonance frequency, a series of measurements on fullscale models together with a theoretical analysis have been carried out, and a flexible resonator for high power and beam tests is designed and being under construction. They will be described in detail as follows.

The Resonator Structure

The rf structure of an integral splitring RFQ is shown in fig. 2. It consists of a base bar, a number of pairs of right-wound and left-wound arms and 4 rod quadrupole electrodes, which in this case have the shape of small vanes. This alternative to the rod electrodes can be inserted without change of the rf structure[4]. The rf structure consists of an array of spiral arms carrying the rod electrodes. Each arm can be regarded as a spiral stem or each pair of arms as a splitring. They are integrated by both the

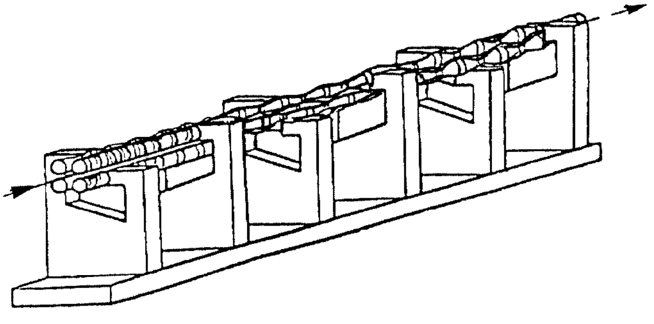

Fig.1 Scheme of a Frankfurt 4-Rod RFQ structure

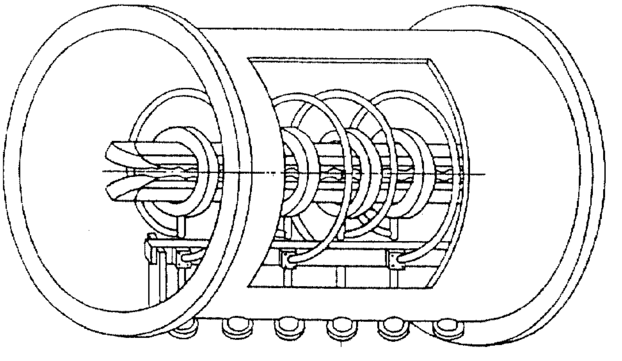

Fig.2 The Integral Split Ring RFQ

---

* Supported by NSFC (Natural Science Foundation of China)

base bar at one end and the four rod electrodes at the other end. Each arm can be treated as a loaded $\lambda/4$- resonator and the base bar as the common ground. The resonator cells are coupled through the mutual inductances of the arms, the coupling capacitances, and the four rods, which correspond to a transmission line which capacitively loads the stems.

Therefore, the resonator can be described as a coupled multi-cell system[13] shown in fig. 3, which can predict the rf properties. This system has a number of different modes, for instance π-0 and 0-0 modes. For the π-0 mode, the operating mode, the neighbour cells resonate in opposite phase and the 4—Rod electrodes are excited to provide the required electric field. If the four rods have modulated longitudinal section (e.g. with the shape of trapezoidal or small vanes as shown in fig. 4), there are not only radial and azimuthal quadrupole fields but also axial field components, which can be used for acceleration. With such an electrode cross section not only the basic quadrupole term will be excited but also higher multipole terms. Because their influence can be neglected for most applications, only the basic terms can be taken for the design calculations as if the rod electrodes would have ideal hyperbolic cross sections.

The 0-0 mode corresponds to a resonance for which all the cells are in phase and there is no voltage between the electrodes. From the equivalent circuit both the resonance frequencies of π-0 and 0-0 modes can be derived:

$$\omega_{\pi 0}^2=\omega_S^2(1+FK_1)/(1+FK_C+2C_qK_C/ND)$$

$$\omega_{00}^2=\omega_S^2(1-FK_1)/(1-FK_C)$$

where $\omega_S^2=2L/((C+2D)(L^2-M^2))$ $K_1=M/L$, $K_C=2D/(C+2D)$ and $F=1-1/N$

The specific impedance ρ can be calculated according to the current distribution along the split ring arm[14]:

$$\rho=16L_eS\sin^2\varphi/(NR_u(1+KS)(C_e+4Q\sin^2\varphi/N))$$

$$Q=2\omega_{\pi 0}L_e/(R_u(1+KS))$$

Where L_e, C_e are equivalent impedances, R_u is the specific resistance and S the length of the splitring or spiral arms. These formulae have been used to analyse the rf properties and optimize the integral splitring RFQ.

For the purpose of ion implantation, adjustable output energy is preferably considered. One way for this is to vary the operating frequency. There is the possibility to realize it for this RFQ structure with a short circuit bar to change the effective length of the arm, corresponding to change the inductance and capacitance of the cell in fig. 3. Since the rf structure is integrated and is adjustable in the cavity tank through stems, it is convenient to assemble and to align the RFQ structure outside the tank[4]. In addition the integrating of arms has greatly improved the rigidity of the rf structure. If it is necessary to further improve the rigidity, a number of pairs of conducting bars can be added to the arms in phase, and there will be only a little influence on the operating mode.

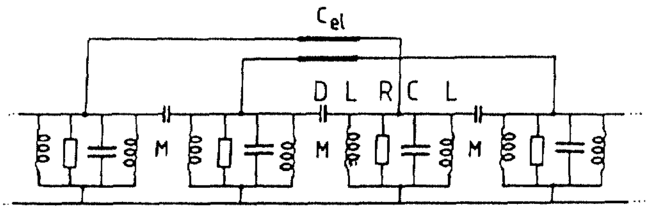

Fig.3 Equivalent curcuit of an Integral Split Ring RFQ

Measurements

To investigate the properties of the integral splitring RFQ experimentally a series of full scale models has been made and measured. The models are made of copper and aluminium. The diameter of the cavity tank is 50 cm. For different purposes there are three groups of measurement to be carried out.

The first group of measurement is to study the basic properties, such as the electric field distribution, operating frequency $f_{\pi 0}$, values of Q and ρ and their dependence on the number N and length S of the split ring "arms", and of electrode aperture radius a. In the measurements the electrodes are cylindrical rods with conical varying diameter from 1.2 to 2.4 cm and a constant periodic length of 2.4 cm. The length of the rods is 66.4 cm and the diameter of the splitring tubes is 2.2 cm. The electrical fields were measured with the bead perturbation method. Results are listed in table 1. The data show that the integral splitring RFQ is suitable to operate below the frequency of 100 MHz, even below 30 MHz, while keeping the mechanical rigidity.

The rf structure has been assembled and fixed by screws only, without any soldering or brazing. This allows simple variation of parameters but will increase the rf power losses even though the values measured are still acceptable. From the data it can be confirmed that the frequency $\omega_{\pi 0}$ of the operating mode decreases with increasing lengths of S of the splitring arms and decreasing electrode aperture a. This can be explained easily by the corresponding capacities and inductivities in the formula for the frequency $\omega_{\pi 0}$.

To determine the length of arm for the high power and beam test resonator, RFQ structures with different length of arm have been measured. The split ring rf structure is always the same (tube diameter 30mm). The results are listed in table 2.

In the measured range of the arm lengthes, an empirical linear formula has been found (see table 2), which fits the experimental data very well. With the formula the arm length can be determined to reach the designed operating frequency through interpolation.

To investigate the rf properties of the variable frequency structure with small vane electrodes, a serious measurement has been carrried out. The longest arm length is 84.5 cm, then the arm can be shortened by moving a short circuit bar (see fig. 5). The preliminary results are listed in table 3. It demonstrates that with reducuing arm length Se, frequency $f_{\pi 0}$ can be increased, while ρ value is decreased. For small changes of the frequency the efficiency is nearly constant.Therefore, this can be used to adjust the resonance frequency. For larger changes of the frequency the problems are not yet solved. In this group of measurement a supporting ring was added at each end of the electrodes. The ring combined the long opposite cantilevered

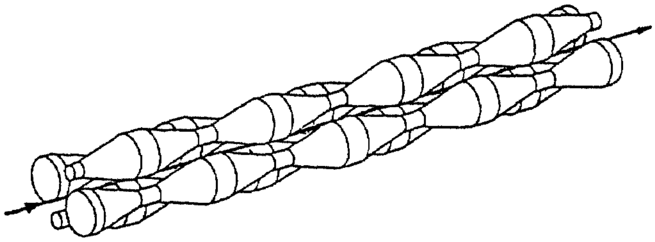

Fig.4 Conically shaped Rod electrodes

electrodes and made them mechanically more stable. The result showed that the ring will make only $f_{\pi 0}$ a little lower (compare table 3 with table 2 for arm length of 84.5 cm). Therefore, it will be adopted for the test resonator.

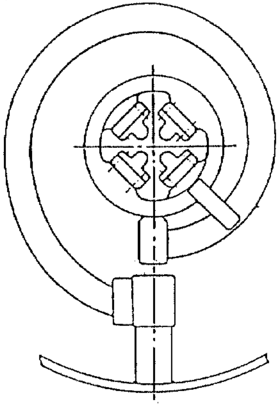

Fig.5 The RFQ with a short curcuit bar

Test Resonator

Cold measurement showed that the integral splitring RFQ seems well suited to operate at low frequency and offers the possibility to adjust the frequency. For further studies of this type of RFQ a resonator for high power and beam tests has been designed and is being constructed now. The mechanical structure is made flexible. For example, the small vane electrodes and arms can be exchanged, because they are assembled and fixed by screws (no soldering or brazing). Therefore we can use different electrodes including unmodulated ones for the high power tests.
To reach better value of ρ of the test resonator than that of models, we will improve rf contacts. To study the rf property of the resonator in case of high duty factor the electrodes and arms are cooled by water. We will further optimize the RFQ structure for the high power test with the existing 26 MHz 50kW transmitter. As a second step a first beam test will be prepared. For this purpose beam dynamic calculations have been done to illustrate the acceleration of heavy ions with the RFQ. Input values are $f_{\pi 0}$ = 26 MHz T_{in} = 35 keV and a specific charge of $q/m = 1/14$ (N^+ ions). The length of electrodes is limited by the existing cavity tank with a length of 90 cm. The calculated results are an electrode length of 87cm, electrode voltage of 70kV, final energy 300 keV and a transmission of 95% up to an N^+ ion current 5 mA.

Conclusions

This preliminary study of the integral splitring RFQ including rf structure, cold measurement, equivalent circuit and beam dynamic calculations showed that this RFQ seems well suited for acceleration of heavy ions at low frequency. It has the advantage of moderate size, good stability, acceptable efficience and convenient manufacture. We will build an RFQ resonator for a high power test with the existing 26 MHz, 50 kW transmitter. Then a beam test will be prepared to accelerate N^+ to 300 keV with the integral splitring RFQ.

Acknoledgements

We thank Prof. Klein (Univ. Frankfurt) for his support and Mr. Pan Oujia (now at Univ. Frankfurt) and Mr. Zeng Baoqing for their assistance.

No	N	S [cm]	a [mm]	$f_{\pi 0}$ [MHz]	Q	ρ [kΩm]
1	8	44.2	5	41.30	1639	91
2	6	44.2	5	37.88	1612	95
3	4	44.2	5	33.15	1517	110
4	6	116.0	7.5	24.01	1086	169
5	6	116.0	6.5	23.03	1028	180
6	6	116.0	5	21.54	1016	197
7	4	179.	7.5	16.27	1261	244
8	4	179.0	6.5	15.54	1233	236
9	4	179.0	5	14.67	1202	190

Table 1 Measured rf properties versus parameters.
Diameter of the tank : 50 cm, N = number of arms,
S = length of arms, a = radius of aperture

S [cm]	84.5	107.8	135.1	179.9
$f_{\pi 0}$ [MHz]	26.27	21.54	18.4	14.85
$f_{\pi 0}S$ [MHz·cm]	2222	2322	2451	2672
$f_{\pi 0}S^*$ [MHz·cm]	2218	2327	2455	2666

Table 2 : Frequency $f_{\pi 0}$ versus length of arm. N = 6, a = 9 mm
*Calculated by $f_{\pi 0}S$ = 1820 + 4.7 S [MHz·cm]

No	N	S_e [cm]	a [mm]	$f_{\pi 0}$ [MHz]	Q	ρ [kΩm]
1	6	29.5	9	40.82	1201	99
2	6	39.5	9	36.51	1217	101
3	6	49.5	9	33.38	1113	102
4	6	64.5	9	28.62	1022	113
5	6	74.5	9	26.15	1046	135
6	6	84.5	9	24.79	1078	154

Table 3 Measured results of variable frequency.
Diameter of the tank: 50 cm

References

1. I.M. Kapchinskij, V.A. Teplyakov, Prib.Tekh.Eksp. No.4 (1970) 19
2. R.H. Stokes, T.P. Wangler, K.R. Crandall, PAC 81, IEEE NS28(1981)1999
3. H. Klein, PAC 83, IEEE NS30 (1983) 3313
4. A. Schempp et al., NIM B10/11 (1985)831
5. R.W,. Müller, Linac 89, BNL 51143 (1979)148
6. A. Schempp et al., PAC 87, IEEE 87CH2387-9(1987)267
7. A. Schempp et al., PAC 83, IEEE NS30 (1983) 3536
8. A. Schempp, H. Deitinghoff, A. Kipper, NIMA278(1989)169
9. R.H. Stokes et al., PAC 83, IEEE NS30 (1983) 3530
10. A. Schempp, NIM B40/41(1989)937
11. A. Schempp, NIM B50(1990)460
12. J. Fang, C.E. Chen, PAC 85, IEEE NS32 (1985) 2981
13. J. Fang, "An Eqivalent Curcuit Model of the Integral Splitring RFQ" Int. Rep., Univ. Peking 1987
14. E. Müller, J. Fang, Int. Rep.81-15, Univ. Frankfurt 1981