INTEGRAL SPLIT RING RFQ STRUCTURE FOR HEAVY ION ACCELERATION

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Abstract

A 4-Rod RFQ structure based on the Integral Split-Ring resonator is being studied for the acceleration of heavy ions. The special features of the structure, rf properties and results of beam dynamics calculations and model tests are described. The results show that this structure is well suited for a low frequency heavy ion RFQ, for which parameters of a prototyp RFQ accelerator for N^+ are presented.

Introduction

The radio frequency quadrupole (RFQ) principle was proposed by Kapchinskiy and Teplyakov [1] in 1970 and successfully tested with a Four Vane cavity in 1980 at LANL[2]. Since then the RFQ has been worldwide developed due to its outstanding features. The RFQ has the multi-functional capability of simultaneous matching, bunching, accelerating, and radially focusing ion beams. RFQs can capture nearly 100 % of an intense ion beam injected at a few keV/nucleon and can accelerate it with little emittance growth up to appr. 1 MeV/nucleon. Now Four Vane RFQs are commonly used to accelerate light ions [3].

With the increasing interest in the use of heavy ions e.g. for inertial fusion and ion implantation 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 Four 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 meters. Fortunately there are two new RFQs, which are suitable to accelerate heavy ions, namely the 4Rod RFQ (or λ/2 RFQ) developed at the University of Frankfurt and the Split Coaxial RFQ at GSI.

The 4Rod RFQ consists of the four rod electrodes together with a row of supporting stems which can be excited to provide the quadrupole field. A 4Rod RFQ with straight stems for 202 MHz has successfully accelerated a 35 mA proton beam at DESY [4]. Figure 1 shows a scheme of this structure. The operating frequency of the 4Rod RFQ can be reduced if the straight stems are substituted with longer conductors. Examples are the Spiral 4Rod RFQ investigated at Frankfurt[5] and LANL[6] . Based on the investigation of the conventional splitring resonator the Integral Splitring and Spiral resonator has been developed at Peking University [7]. An Integral Splitring RFQ is formed out of four rod electrodes instead of drift tubes. To investigate its possible use in accelerating heavy ions, the properties of this RFQ structure have been studied experimentally on a series of a half and full scale models together with a theoretical analysis. The results showed that it is well suited to accelerate heavy ions well below the frequency of 100 MHz. It will be described in detail as follows.

Rf Structure and Properties

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 4Rod quadrupole electrodes, which in this case have been the shape of small vanes. This alternative to the rod electrodes can be inserted without change of the rf structure [8].

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 base bar at one end and the four rod electrodes at the other end. From rf point of view, each arm can be treated as a loaded λ/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 by the four rods which correspond to a transmission line which capacitively load the stems.

For the operating mode, the π-0 mode, the neighbour cells resonate in opposite phase and the 4Rod electrodes are excited to provide the required electric field. If the four rods have modulated longitudinal sections (e.g. with trapeziodal shape as shown in fig. 3), there are not only radial and

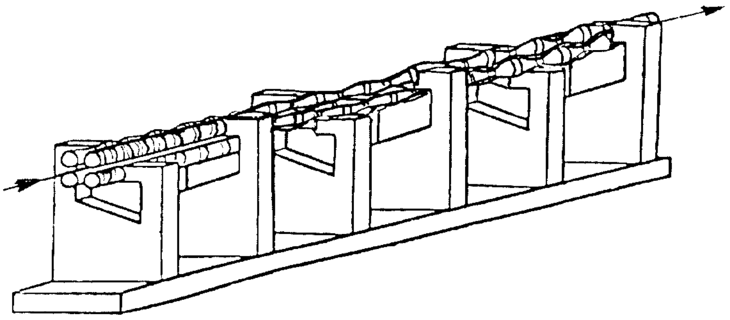

Fig. 1 Scheme of a Frankfurt 4Rod structure

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azimutal 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 exited 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 rf resonator can be described as a coupled multi-cell system, which has a number of different modes. For instance there is the 0-0 mode, which corresponds to a resonance with all the cells in phase and no voltage between the electrodes.The operating mode, the π-0 mode resonates at the lowest frequency. The mode separation and operational stability is very high.

Since the rf structure is integrated and is adjustable in the cavity tank through stems, it is convenient to assemble and to aligne the RFQ structure outside the tank [8]. 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.

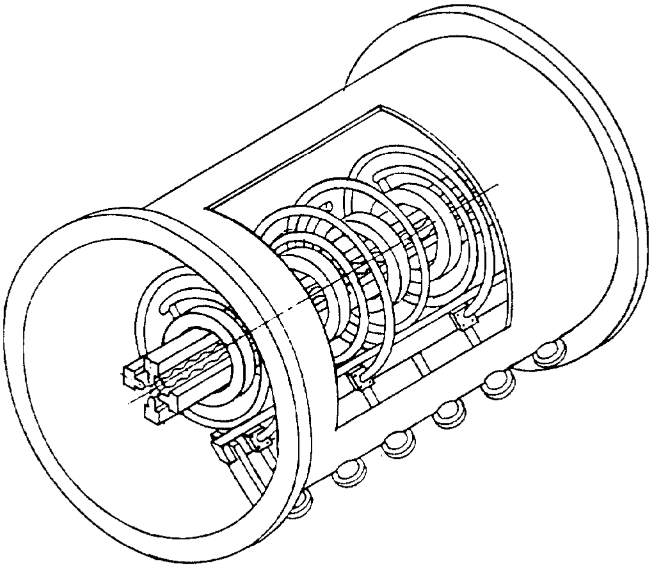

Fig. 2 The Integral Split Ring RFQ

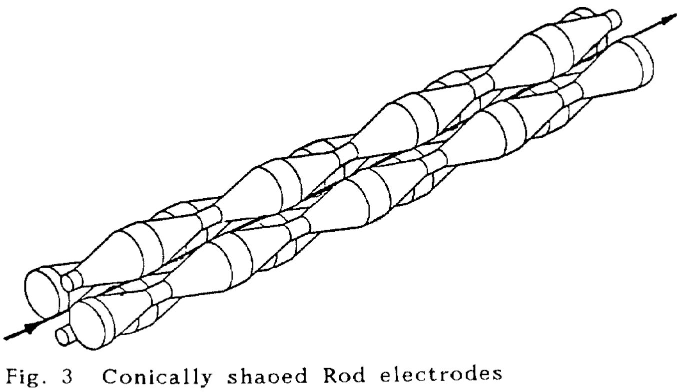

Fig. 3 Conically shaoed Rod electrodes

Lumped Equivalent curcuit

As mentioned above, the Integral 4Rod Split Ring RFQ can be treated as a coupled multi cell curcuit[9,10]. It is similar to the drift tube loaded cavity for which the properties could be predicted well with the equivalent curcuit as shown in fig.4. The difference to the split ring resonator is the 4Rod transmission line instead of the drift tubes. For the π-0 mode this can even be simpified by a simple capacity because the voltage distribution is nearly uniform. The resonance frequency of one cell is:

$\omega_s^2 = 2L/((C+2D)(L-M)$,

Solving for the π-0 mode:

$\omega_{\pi o} = \omega_s(1+FK_1)/(1+FK_c+2C_qK_c/ND)$

where $K_1 = M/L$, $K_c = 2D/(C+2D)$, $F = 1-1/N$

The impedance ρ can be calculated according to the current distribution along the split ring arm.

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

$Q = (\omega_{\pi o}Le/R_u)/(1+KS)$ where Le, Ce 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 split ring RFQ.

Model tests

To investigate the properties of the integral Split Ring RFQ experimentally a series of half and full scale models have been made and measured. The models are made of copper and aluminium. 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 split ring arms is 2.2 cm. Electrical fields are measured with bead pertubation method Part of the data is listed in Table 1. The data shows that the integral Split Ring 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 scews 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 $\omega_{\pi o}$ of the operating mode decreases with increasing lengthes S of the Split Ring arms, and decreasing electrode aperture a. This can be explained easily by the corresponding capacities and inductivities in the formula for the frequency $\omega_{\pi o}$.

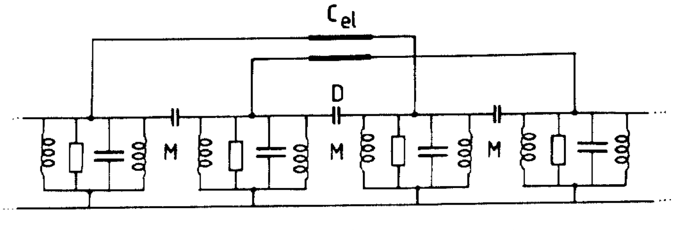

Fig. 4 Equivalent curcuit of Integral Split Ring RFQ

Based on this experimental data a series of beam dynamic calculations was done to illustrate the acceleration of heavy ions with the RFQ. Input values are $f_{\pi o}$= 26 MHz, T_{in}= 35 keV, and a specifc charge of q/m= 1/14 e.g. N^+ ions. For the spcific impedance a very low value of ρ = 150 kΩm has been taken. Higher field harmonics have been neglected in the calculation. The group of results listed in Table 2 shows a very good beam transmission.

We want to further optimize our RFQ structure for a high power test with the existing 26MHz 50 kW transmitter. In a second step a first beam test will be prepared. For this purpose design studies have been done for a RFQ, which fits into an existing tank with a length of 90 cm. Therefore the transmission efficiency or the final energy must be reduced compared to the values of Table 2.

Figure 5 shows that the transmission depends on the accelerator length (final energy 400 keV) so that for the design presented in Fig. 6 a transmission of 70% has been calculated which is a reasonable value for a short test RFQ accelerator.

Conclusions

This preliminary study of the integral Split Ring RFQ including rf structure model tests, equivalent curcuit and beam dynamic calculations showed, that this RFQ seems well suited for acceleration of heavy ions at low frequencies. It has the advantage of moderate size good stability acceptable efficiency and can be manufactured also without numerical controlled machines.

We will built a 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 400 keV with the Integral Split Ring RFQ.

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References

1. I.M. Kapchinskij, V.A. Teplyakov, Prib.Tekh.Eksp., No. 4, 1970, p.17, p.19
2. R.H. Stokes, T.P. Wangler, K.R. Crandall, PAC 81, IEEE Ns 28, No.3, 1981, p. 1999
3. H. Klein, PAC 83, IEEE Ns 30, 1983, p 3313
4. A. Schempp et al., PAC 87, IEEE 87CH2387-9, 1988, p. 267
5. R. Stokes et al., PAC 83, IEEE Ns30, 1983, p.3530
6. A. Schempp et al., PAC 83, IEEE Ns30, 1983, p.3536
8. A. Schempp et al., NIM B10/11, 1985, p. 831
7. J.X. Fang, C.E. Chen, PAC 85, IEEE Ns 32, 1985, p. 2981
9. J.X. Fang, "An Equivalent Curcuit Model of the Integral Splitring RFQ", Internal Memo, Peking University, 1987
10. E. Mueller and J. Fang, Int. Rep. 81-15, IAP Frankfurt, 1981

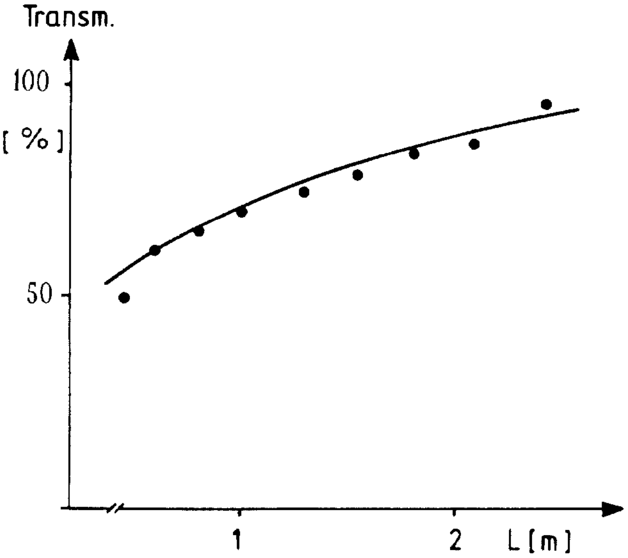

Fig. 5 Beam transmission as function of the RFQ length

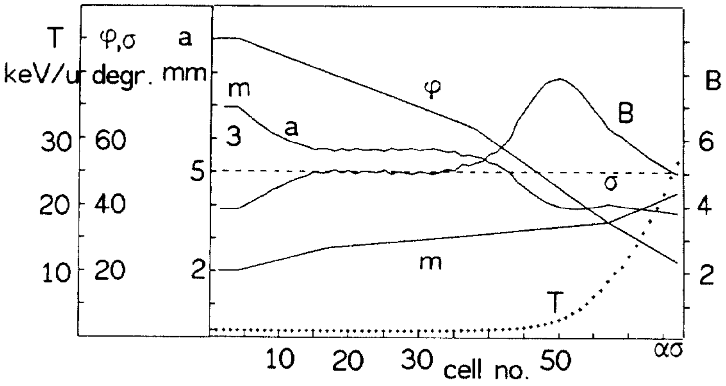

Fig. 6 Layout of a short 400 keV RFQ for N^+

No.	D mm	N	S cm	a mm	$f_{\pi o}$ MHz	Q	ρ kΩm
1	24	6	25.8	5	87.59	1406	43
2	50	8	44.2	5	41.30	1639	91
3	50	6	44.2	5	37.88	1612	95
4	50	4	44.2	5	33.15	1517	110
5	50	6	116.0	7.5	24.01	1086	169
6	50	6	116.0	6.5	23.03	1028	180
7	50	6	116.0	5	21.54	1016	197
8	50	4	179.0	7.5	16.27	1261	244
9	50	4	179.0	6.5	15.54	1233	236
10	50	4	179.0	5	14.67	1202	190

Table 1 Model parameters and measured results
D = Diameter of the cavity, N = number of arms
S = length of arms, a = aperture

No.	L m	n	P kW	T keV	Tr %
1	1.12	57	37	307	98
2	1.35	64	44	394	98
3	1.57	69	50	509	97

Table 2 Dynamic calculations for 26 MHz and N^+
L = length of cavity, T = output energy
n = number of cells, Tr.= transmission efficiency