An Integral Splitring Resonator Loaded with Drift Tubes & RF Quadrupoles

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Summary

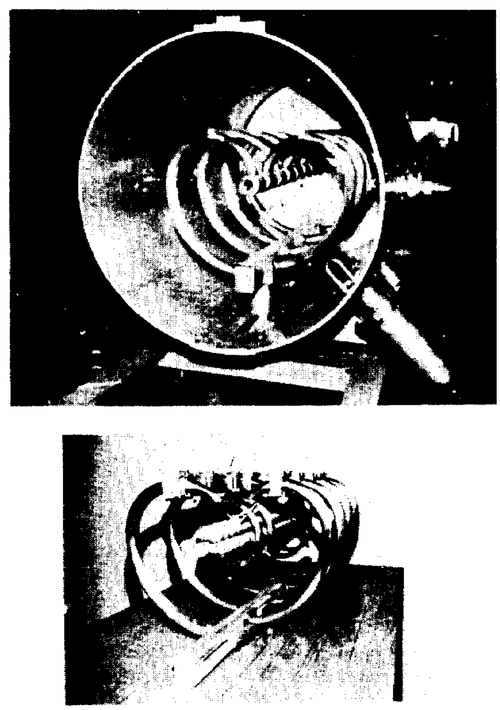
In order to improve the mechanical stability, the coupled splitring (also spirals) resonators, loaded either with drift tubes or RF Quadrupoles, are integrated together through conducting bars. Investigations on 1/2 and full scale models (50 cm in tank diameter) show considerable improvement on the overall rigidity of the structure while keeping the RF efficiency high. The operating frequency can be greatly reduced by the integration to 24 and 14 MHz for loading with drift tubes and RFQ respectively. The integration also flattens the accelerating voltage distribution and enhances the mode separation and thus facilitates the assembling and commissioning of the accelerating structure. An equivalent circuit of the integral splitring, which agrees well with the experiments, has been developed.

Introduction

The conventional splitring and spiral resonators with drift tubes have the merits of moderate size, simple structure and good efficiency and have been successfully used as the accelerating structures of post linear accelerators in many laboratories [1-4], while RFQ structures with spiral stems have also been developed in a number of laboratories in recent years [5]. They are very suitable to operate at low frequency for accelerating heavy ions. To achieve stable operation, both the splitring (or spiral) resonator and the spiral RFQ need good enough mechanical rigidity so that the mechanical vibration caused by pondermotive force and mechanical noises can be negligible. However for the case of low frequency the rigidity could be weakened due to the long arms of the structure. In order to keep high stability even though at low frequency, an integral splitring resonator has been developed. This type of resonator is actually a modified coupled structure of conventional splitring or spiral resonators and it can be loaded either with drift tubes or RFQ. A series of 1/2 and full scale models have been constructed and tested. Meanwhile a lumped equivalent circuit was developed and compared with the experiments.

Structure and Properties

The integral splitring resonator is actually a coupled resonator. Usually a multi-cell coupled resonator is good for increasing the RF efficiency of the structure, though the number of the cells must be choosen as a compromise between the RF efficiency and the reduced flexibility of energy variation. However the integral splitring structure not only leads to sufficient RF efficiency, but also higher stability in operation as well as other performances. Actually this structure differs from the conventional coupled splitring mainly in that the cells are directly connected together into an integral structure by several conducting bars. The bottom bar is used to combine all the conventional splitrings together at the lower ends of each arm, while two top bars, which play most important role in improving rigidity and RF properties, are connected to the splitring loops at their top end; one bar for right-wound arms and another bar for left-wound arms. Between the top and bottom bars several additional pairs of combining bars can be added if it is necessary to further increase the rigidity of the structure. Thus the integral structure is formed like a trussed frame. In this structure, all the arms are made perpendicular to the combining bars and the drift tubes or RFQ electrodes can be mounted at their ends near the top bars as in the case of conventional spirals. As a result of integrating, the rigidity of structure is considerably improved. In addition, the bottom bar also offers a better conduction to RF current for all cells so that one can even leaves out the original legs from each ring loop if the cooling water goes through the bottom bar. The full scale model of integral splitring loaded with drift tubes and RFQ are shown in Fig. 1 a and b respectively. It can be seen that the structure can be conveniently assembled outside tank as a whole and easily mounted into the tank through a number of legs. Apart from the mechanical property, the integration also improves the RF behaviour of the structure. Usually there are N modes in a conventional coupled resonator containing N electromagnetically coupled cells, and the accelerating voltage distribution between drift tubes is not flat (Fig. 2). But in the integral N-cell splitring resonator with top bars, only π and 0 mode exist and the accelerating voltage distribution is flattened (Fig. 2). Meanwhile the integration keeps RF efficiency reasonably high. These will be described in detail later on.



(a)

(b)

Fig. 1. Integral splitring resonator
a) Resonator with drift tubes, b) Frame with RFQ

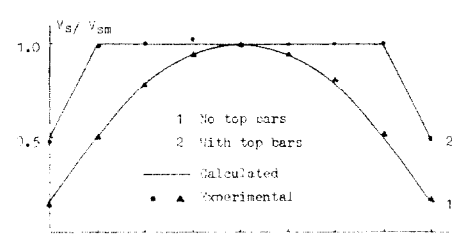


Fig. 2. Accelerating voltage distribution in gaps

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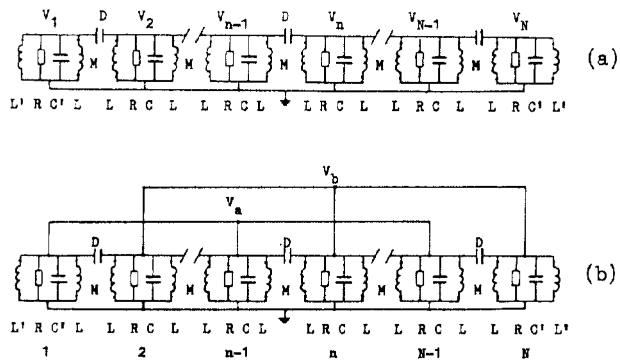


Fig. 3. Equivalent circuits
a) Without top bars, b) With top bars

Lumped Equivalent Circuit

The RF behaviour of the integral splitring resonator can be briefly explained by using a simple lumped circuit. The lumped equivalent circuit for the case without the top bars is shown in Fig. 3a. For simplicity, the cells are considered uniform and each couples only with its closest neighbours. Each of the N cells is corresponding to an arm with a drift tube. The end cells of both sides are changed a little by the end effect :

$$L' = L(1 - M^2/L^2), \qquad C' = C(1 + D/C)$$

When Q value is high enough, i. e. $Q \gg \omega_s/\omega$,

where $Q = \omega_s(C + 2D)R$,

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

the mode frequencies and voltage distribution along the chaincircuit can be solved from the Kirchhoff's equations as follows [6] :

$$\omega_q^2 = \omega_s^2(1 - K_i \cos\phi_q)/(1 - K_c \cos\phi_q)$$

$$V_{qn} = A_q \sin n\phi_q$$

$$K_i = M/L, \qquad K_c = 2D/(C + 2D)$$

$$\phi_q = q\pi/(N + 1), \qquad A_q = \text{const}$$

$$q, n = 1, 2, \cdots, N$$

The voltage in the S -th gap is :

$$U_{qs} = B_q \cos((2S + 1)\phi_q/2)$$

$$S = 0, 1, \cdots, N. \qquad B_q = \text{const}$$

The results above indicate that there are N modes for a resonator which contains N coupled cells. As an example, the calculated mode frequencies and voltage distribution of an integral splitring resonator of 8 cells without top combining bars are illustrated in Fig. 4. It agrees well with the experimental results.

As for the function of the top combining bars, if concentrating on accelerating mode, it can be simply considered as adding the conducting wires to the corresponding cells as shown in Fig. 3b. Thus only π and 0 modes can exist, the mode frequencies and voltages are [6]:

for π mode, $\omega_\pi^2 = \omega_s^2(1 + F K_i)/(1 + F K_c)$

$$V_a = -G V_b$$

for 0 mode, $\omega_0^2 = \omega_s^2(1 - F K_i)/(1 - F K_c)$

$$V_a = G V_b$$

where $F = 1 - 1/N, \quad G = 1,$ if N is even

$F = G = (1 - 1/N)/(1 - 1/N^2)^{1/2},$ if N is odd

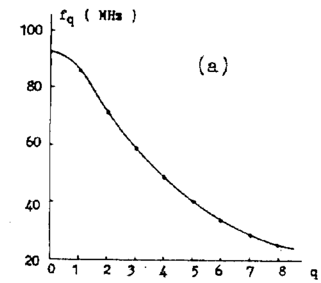


Fig. 4
a) Mode frequencies
b) Mode voltage in gaps
N = 8, no top bars
——— Calculated
• Experimental

The chaincircuit shown in Fig. 3b can also simply be used to RFQ loading, if the D is considered as the piecewise coupled capacitances between the two pairs of RFQ electrodes.

There might be more factors that should be taken into account in practice. For instance, the finite cross section of the top bars may reduce the resonant frequencies. In addition, the assumption of closest neighbouring coupling is not met quite well in some cases. Hence the RF behaviour of the integral splitring resonator can not be wholly derived from a simple lumped chaincircuit like Fig. 3, nevertheless the principal behaviour, especially for the accelerating mode, have been illustrated well by these chaincircuits. So the equivalent circuit should be helpful to the study and design of the integral structures if the parameters have been determined previously [7,8].

Experimental Studies

Extensive studies were carried out experimentally to show various effects of the combining bars on the RF properties of the cavity. As the first phase, a series of small model resonator (24 cm in tank diameter) of both integral and conventional coupled splitring were constructed, tested and compared carefully with each other so as to determine if the integral structures are suitable to be used as an accelerator structure and whether its RF properties can be competitive with the conventional ones. After a great deal of systematic measurements, the answer is affirmative and satisfactory. Then the second phase of the experiment was followed to get accurate data for the actual integral splitring resonators. Finally, a series of full scale model resonator (50 cm in tank diameter) were constructed and tested.

The tube diameter for the full scale loop arms is 2.2 cm, and the dimension for the drift tubes are : length 5.85 cm, outer diameter 3.85 cm, inner diameter 1.8 cm, inner gap 2.0 cm and end gap 1.0 cm. All the structures are either made of copper or aluminium. In the experiments, great care were given to ensure accurate assembling and good RF conduction so as to

Table 1. Experimental Results with Drift Tubes

No.	1	2	3	4	5*
D of tank(cm)	50.0	50.0	50.0	50.0	50.0
L of tank(cm)	64.0	64.0	64.0	64.0	64.0
N of arms	8	8	8	8	8
L of arms(cm)	44.2	44.2	182.3	182.3	44.2
f_π (MHz)	102.66	98.14	24.95	24.28	101.15
Q	5800	5248	2626	2529	5813
R_p (MΩ)	53.0	50.2	43.9	40.3	49.3
Z (MΩ/m)	82.8	78.4	68.6	63.0	77.0
Top bars**	No	Yes	No	Yes	No

D - Diameter, L - Length, N - Number
* Conventional coupled splitring
** With cross section of 1.8 x 1.0 cm^2

Table 2. Experimental Results with RFQ

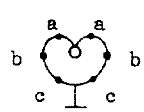
No.	1	2	3	4	5
D of tank(cm)	24	50	50	50	50
L of RFQ (cm)	28.8	66.4	66.4	66.4	66.4
N of arms	6	4	4	4	4
L of arms(cm)	25.8	44.2	179.0	179.0	179.0
D of aper.*(cm)	1.0	1.0	1.0	1.25	1.5
f_π (MHz)	87.59	33.15	14.67	15.54	16.27
Q	1406	1571	1202	1233	1261
ρ (KΩ · m)	43.2	110.4	190.0	235.6	243.8

* aper. - aperture

Table 3. Influence of combining bars on f_π and Z *

		single tube		double tubes	
No.	bars**	f_π(MHz)	Z(MΩ/m)	f_π(MHz)	Z(MΩ/m)
1	a	190.73	85.6	204.79	73.3
2	ab	189.07	74.4	204.25	65.5
3	abc	188.91	73.7	203.10	58.1
4	abc	191.79	76.3		

* On 1/2 scale model resonators (with 6 drift tubes)
** Cross section of each bar :
No. 1,2,3 - 5 x 2 mm^2
No. 4 - Dia. 1.5 mm wire



achieve a nice stable structure at lower frequency with high efficiency. In addition to the structure loaded with drift tubes, trapezoidally modulated RFQ electrodes loading was also tested. Some typical results of the experiments are listed in Table 1 - 3 and illustrated in Fig. 2,4,5. The field distribution in all cases were measured by well known method of bead perturbation.

The parallel resistance R_p , shunt impedance Z and specific R_p-value ρ in the list are defined as follows.

$$R_p = (\int |E| dz)^2 / P = Z\,l , \quad \rho = l\, V^2 / P$$

P - dicipated RF power in the resonator
V - the voltage between two pairs of RFQ electrodes
l - the length of the cavity

For the case of integral splitring loaded with drift tubes, R_p or Z are nearly as high as that of the conventional coupled splitring cavity, provided that its combining bars are not too thick (Table 1, No.2 and 5). The ratio of R_p to the number of drift tubes, N, are nearly kept constant as N varies, while the

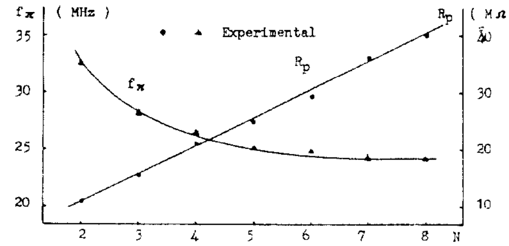


Fig. 5. R_p and f_π vers. number of drift tubes (with top bars except N = 2)

frequency f_π reduces with increasing N (Fig. 5). As for the integral structure with RFQ loading, its ρ value are good enough at low frequencies (Table 2, No. 3 - 5). The experiments also showed that the RF efficiencies and frequencies decrease slowly with the increase of either the number or the cross section of the combining bars (Table 3, No. 1 - 4). In addition, the frequencies f_π can also be reduced by increasing the equivalent parameters including inductance L, capacitance C, mutual inductance M or coupled capacitance D, as the equivalent circuits show. As for the gap voltage distribution along the axis, it has been considerably flattened by top bars as can be seen from Fig. 2 The axial and radial field distribution for the RFQ loading structure are also very satisfactory.

The RF behaviour for an integral structure consisted of two parallelly wound tubes, with a higher rigidity, does not show much change from the case of single tube (Table 3, No. 1 - 3).

Conclusion

The integral splitring resonator loaded with drift tubes or RFQ electrodes improves considerably the overall rigidity of the structure comparing to the conventional coupled splitring or spiral resonators. This will be in favour of a stable operation with good RF efficiencies especially for low frequency structures, which are most suitable to accelerate low energy heavy ions either by drift tubes or RFQ. In addition, the integral splitring structure has the merits of flattened voltage distribution, enhanced seperation and the convenience of assembling and comissioning. The power test for the further study of this integral structure is in progress.

Acknowledgement

The authors wish to thank Prof. F. C. Yu for his kind advices. The effective cooperation of Mrs. J. L. Yuan is also gratefully acknowledged.

References

1) J. M. Brennan, C. E. Chen, et al, Bulletin of American Physical Society, Vol. 28, 2 (1983) 91
2) J. M. Brennan, C. E. Chen, et al, IEEE Trans. NS-30, 2798 (1983)
3) L. M. Bollinger, IEEE Trans. NS-30, 2065 (1983)
4) M. Grieser, et al, IEEE Trans. NS-30, 2095 (1983)
5) H. Klein, IEEE Trans. NS-30, 3313 (1983)
6) J. X. Fang, "An Equivalent Circuit Model of the Integral Splitring Resonator", Int. memo. Peking University, 1984
7) E. Mueller, J. X. Fang, Int. Rep. 81-15, Institut fuer Angewandte Physik der Universitaet Frankfurt a. M. , 1981
8) E. Mueller, H. Klein, Nucl. Inst. Meth. 224, 17 (1984)