

EXPLORING THE FEASIBILITY OF A SEPARATED FUNCTION RFQ STRUCTURE*

C.E. Chen, X.Q.Yan, J.X. Fang, Z.Y. Guo, W.G. Li, IHIP, Peking University, Beijing, China
Y. Wu, IPP, CAS, Hefei, China

Abstract

The accelerating field in the conventional RFQ is originated by the surface modulation of the quadrupole electrodes. However, the axial accelerating field generated in this way is quite limited. To enhance the energy gain, an alternative structure called Separated Function RFQ (SFRFQ) was proposed, and the feasibility of which is being explored. The RF accelerating field in the SFRFQ structure mainly occurs at gaps between periodical cells, while the electrical quadrupole field inside the cells provides the transverse focusing. Two kinds of structures, namely SFRFQ with diaphragms and with mini-vane gaps, have been studied. It turns out that the energy gain can be improved considerably, comparing with that of conventional one. All the preliminary results of calculation and measurements are presented and discussed in the paper.

1 INTRODUCTION

RFQ accelerator integrates beam acceleration, bunching and transverse focusing in one compact structure and is able to accelerate tens or hundreds mA of beam from ion source to several MeV. As a type of low energy high current linear accelerator it has been extensively used in a great number of areas since 1980's. RFQ group at Peking University has developed 26 MHz high duty factor heavy ion Integrated Split Ring type RFQ with mini-vane water-cooled electrodes since 1984 [1], while 4-vane structures has been developed in many laboratories elsewhere for working at higher frequency to accelerate light ions.

The RFQ accelerator elegantly makes best use of the surface modulation of electrodes so that an axial accelerating field can be superimposed on to the quadrupole field. However, the axial accelerating field generated in this way is quite limited, as the enhancement of the modulation will not always gain much in E_z , especially if it's maximum is being approached. On the other hand, the higher the axial field maximum means the less the transverse focusing factor. Based on the experiences of 1 MeV ISR RFQ at Peking University [2], an alternative structure was proposed to enhance the energy gain. The idea is to separate the axial field from the quadrupole field and to accelerate ions with a series of periodically loaded gaps. The RF accelerating field in the SFRFQ structure mainly occurs at gaps between cells,

while the electrical quadrupole field inside the cells provides the transverse focusing. We called this kind of structure the Separated Function RFQ (SFRFQ), and the feasibility of which is being explored [3]. Two kinds of structures, namely SFRFQ with diaphragms and with mini-vane gaps, have been studied theoretically and experimentally. In both cases, the over all performance turns out to be improved, comparing with that of the conventional RFQ.

2 THE FIELD OF CONVENTIONAL RFQ

As for the conventional RFQ, the axial and transverse field generated by surface modulated electrodes can be expressed as follows (see fig.1)

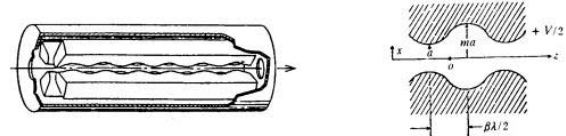


Fig. 1 Electrode profile of the conventional RFQ

$$E_z = (kAV/2) \cdot I_0(kr) \cdot \sin kz \cdot \sin(\omega t + \phi) \quad (1)$$

$$E_r = [- (FV/a^2) \cdot r \cdot \cos(2\psi) - (kAV/2) \cdot I_1(kr) \cdot \cos kz] \cdot \sin(\omega t + \phi) \quad (2)$$

where V is the inter-electrode voltage, m is the depth of the surface modulation, $k = 2\pi / \beta\lambda$, and A the acceleration factor:

$$A = (m^2 - 1) / [m^2 \cdot I_0(ka) + I_0(mka)] \quad (3)$$

F is the focusing factor:

$$F = 1 - A \cdot I_0(ka) \quad (4)$$

where a is the radius of the beam aperture between electrodes, I_0 I_1 are modified Bessel functions. The energy gain of an ion with a charge of q will then be:

$$\Delta w = q \cdot A \cdot T \cdot V \cdot \cos(\omega t + \phi_s) \quad (5)$$

where T is the transit time factor, normally $T \approx \pi / 4$, ϕ_s is the RF phase of the accelerated ion. It is seen that A actually means the utilization coefficient of the voltage between quadrupole electrodes. A is plotted versus m in

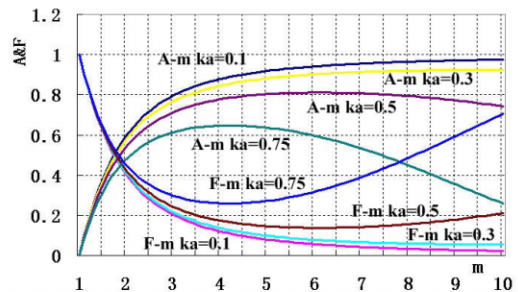


Fig. 2 A & F versus m for conventional RFQ

*Supported by NSFC

Fig.2. Formula (4) and Fig.2 show that if a sufficient focusing factor is essential then the acceleration factor has to be kept around ~ 0.5 . In addition the transit time factor $T < 1$. Hence the energy gain per cell will be rather limited.

3 THE FIELD OF SFRFQ WITH PERIODICALLY LOADED DIAPHRAGMS

The structure of a SFRFQ with periodically loaded diaphragms is shown schematically in Fig. 3, where diaphragms are mounted on to the electrodes with no surface modulation.

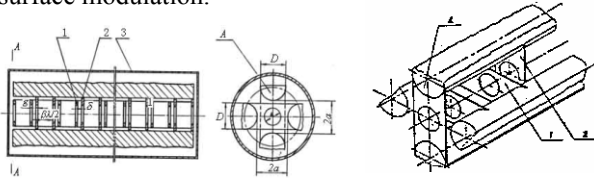


Fig. 3 Schematic view of the SFRFQ structure

(1&2 diaphragms, 3 cavity wall, 4 quadrupole electrodes)

In the SFRFQ, acceleration mainly takes place inside the gaps and the energy gain per cell is

$$\Delta w = q \cdot T \cdot V \cdot \cos(\omega t + \phi_s) \quad (6)$$

where the transit time factor $T \approx 1$. While inside the $\beta\lambda/2$ cell, the focusing factor $F=1$ since $m=1$ and $A=0$. The above argument does imply higher energy gain and stronger transverse focusing.

However, there is a decelerating field at the back of the gap induced by the diaphragm inside the cell. Nevertheless, the effect of the decelerating field depends strongly on the geometry. As a thick diaphragm will shield off some of the decelerating field and also by tuning the thickness of the diaphragm, the RF phase can be adjusted to weaken the effect of deceleration. By using RELAX3D program, the distribution of the axial field is calculated (Fig. 4) which is well consistent with the measurement. The geometrical parameters in the calculation are: $a=0.64$ cm, $d=0.7$ cm, $D=1.4$ cm, $g=0.5$ cm, $\beta\lambda/2=3.9$ cm (refer to Fig. 3) and $V=75$ kV. Based on

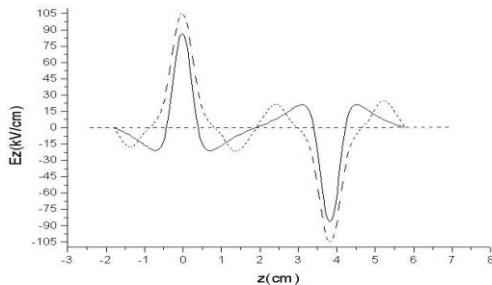


Fig. 4 The axial field distribution of a SFRFQ (Thickness $\delta=0$ real line, $\delta=7.6$ mm dotted line)

the field computation, the energy gain is calculated and the results are compared favourably with that of the conventional RFQ [4].

To further enhance the energy gain, an asymmetrical structure was developed, where one side of the diaphragm pair is stretched to $\sim \beta\lambda/4$ so as to shield off more decelerating field. The schematic view of the structure is shown in Fig. 5a, and the calculated field distribution and the energy gain of the improved version is shown in Fig.5b. The ions will be accelerated inside the gap of the

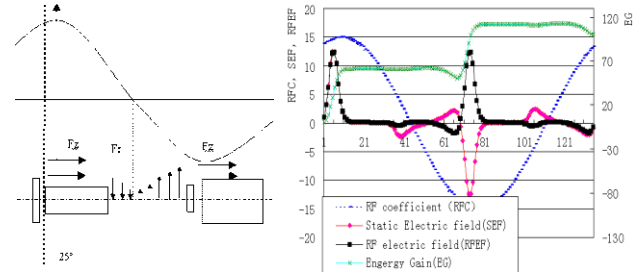


Fig. 5a Schematic view of the asymmetrical SFRFQ(left), 5b Calculated axial field distribution and energy gain(right)

diaphragm pair, and then drift freely in a distance of $\sim \beta\lambda/4$. At the exit, ions will experience some extent of axial decelerating field, and then drift in an alternatively focusing quadrupole field. Before entering the next accelerating gap, the ions will see decelerating field again. Considering the time dependence of the RF field, which is indicated by the dotted line in the figure, the effect of the decelerating field at the diaphragm exit is negligible, while there is a minor energy drop at the entrance of the next gap, which is indicated in Fig. 5b.

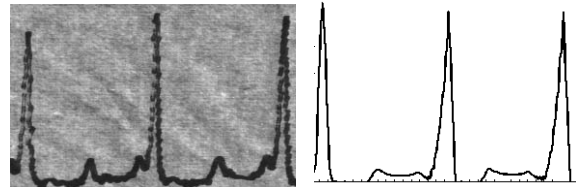


Fig. 6 Measured(left) & calculated(right) axial field $E_z \sim Z$

The calculated field pattern is verified by the measurement on the 26 MHz ISR RFQ test model, and is plotted in Fig.6. The specific shunt impedance measured is $124 \text{ k} \Omega \cdot \text{m}$, and $Q=1390$. The photo of the asymmetrical diaphragms is shown in Fig.7



Fig. 7 The asymmetrical diaphragms

4 THE FIELD OF SFRFQ WITH PERIODICALLY LOADED MINI-VANES

To avoid the decelerating field in the SFRFQ, a structure with periodically loaded mini-vanes of no surface modulation has been studied. Its central part of the structure is shown in fig. 8. (I-I) is a pair of long mini-vanes with no modulation and is supported by ring B, D, and etc. while (II-II) consists of another pair of flat mini-vane series 1,2,3,4, ---. Among them, 2,4,6,--- are supported by ring B, D and etc. at ground potential, while 1,3,5,--- are excited to RF potential V and are supported by ring A, C,---. Therefore, there are accelerating electric field between vanes 1, 3,-- and 2, 4,--. As the length of each short mini-vane is equal to $\beta\lambda/2$ respectively, ions can be accelerated continuously at these gaps. The ions drift inside the odd number vanes will experience focusing by the quadrupole field, but will drift freely inside the vanes with even numbers. This version of SFRFQ does not have any decelerating field.

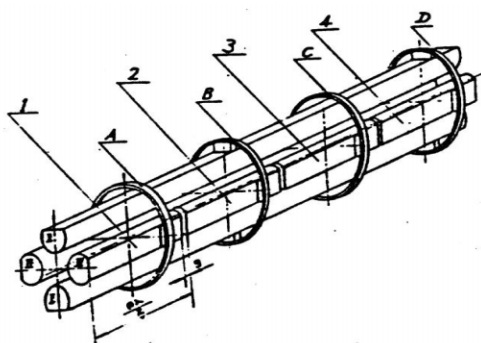


Fig. 8 Schematic view of central part of SFRFQ with mini-vanes

To increase the accelerating field between the vane gaps, a series of diaphragms are attached to both ends of the vanes, inside which ions drift freely in the channel (see Fig.10). With RELAX3D program, the calculated electric field distribution on axis is shown in Fig. 9 in comparing with the measured one, which was obtained on a test model excited by ISR resonators. It is clearly demonstrated that no decelerating field exists. The calculated field distribution has been modified by considering the volume of perturbation cylinder, which is 4mm of diameter and 4 mm of length. The measured specific shunt impedance with diaphragms is 201 kΩ·m which is obviously not bad.

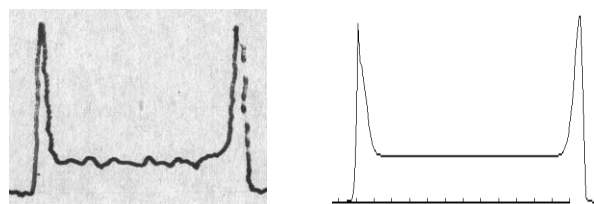


Fig. 9 Calculated and measured field distribution along axis of SFRFQ with mini-vanes.



Fig. 10 Test model excited by ISR resonators

5 CONCLUSIONS

The preliminary results of calculation and model measurement indicate that both kinds of SFRFQ structure may meet the requirements to work in the higher energy region after a conventional RFQ. The parameters are listed in Table 1 for comparing with the conventional RFQ. The Q and ρ are all measured on the ISR RFQ test model, R₀ is the average aperture, while * denotes the best data ever obtained for conventional RFQs. Further studies will be carried out for a SFRFQ after the 1 MeV ISR RFQ [2], including dynamics design and structure technology.

	SFRFQ		Conventional 1MeV RFQ
	Diaphragm	Minivane gaps	
φ_s	-25°	-25°	-25°
R ₀ (mm)	9	9	9
$\beta\lambda/2$ (mm)	68	68	67
Energy input(MeV)	0.95	0.95	0.95
Inter voltage(kV)	70	70	70
Energy gain (keV)	51	32	30
Q- value	1390	1700	1200*
ρ Specific shunt impedance (kΩ.m)	124	201	100*

6 REFERENCES

- [1] J.X.Fang, J.E.Chen, Integral Split-ring Resonator Loaded with Drift Tube and RFQ, IEEE Trans Nucl Sci, NS-32, 2981,1985
- [2] J.E. Chen, J.X. Fang, et al. The Beam Test of a 26 MHz ISR RFQ at Peking University, Proc. of EPAC 1994
- [3] J.E. Chen, J.X. Fang, W.G. Li, Y. Wu, X.Q. Yan, Tentative Idea on Accelerating Structures of SFRFQ, Progress on Natural Science, Vol. 12, No.1, 23, 2002
- [4] X.Q. Yan, J.X. Fang, Y. Wu, J.E. Chen, Study of Reverse Field in Accelerating Structure of SFRFQ with Diaphragm, Bulletin of China Academic Journals, Vol.7, No.11, 1441,2001