THE STUDY OF SEPARATED FUNCTION RFQ (SFRFQ) WITH DIAPHRAGMS*

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Abstract

The accelerating efficiency of conventional RFQ structure is limited by transverse focusing, and the drift tube structure is more efficient when particle energy is higher. Based on the experience on the 26 MHz heavy-ion Integrated Split Ring RFQ (ISR RFQ) with mini-vane electrodes, RFQ group at Peking University has proposed a novel post-RFQ structure, Separated Function RFQ (SFRFQ) with diaphragms. In such a structure the gaps between diaphragms offer higher accelerating field while keeping sufficient electric quadrupole focusing. However, field distribution calculation shows that decelerating fields exist in the structure with uniformly distributed diaphragms. In order to suppress the decelerating fields, a structure called asymmetrical $\beta\lambda/4$ diaphragm SFRFQ was proposed and designed. After that a RF cold model had been constructed to verify the calculation results and to explore the technological feasibility of the structure. The shunt impedance was calculated with Micro Wave Studio (MWS), which turned out that the RF efficiency is enhanced after introducing gaps into RFQ structure, and the total length of the linac can be shortened considerably, which has been proved with dynamics simulations.

INTRODUCTION

As a type of low energy high current linear accelerator RFQs serve well as the first accelerator in a chain of linear accelerators, providing the initial bunching and acceleration of beams. However the accelerating efficiency of RFQ structure is limited, because a large part of RF voltage is used for transverse focusing. Further more the efficiency falls off as the fixed voltage will be applied to the increasing cell length. The drift tube structure has higher rf efficiency only in the range of higher energy, that is why the idea of introducing accelerating gaps into RFQ is also attractive for some applications. For example, SP RFQ [1], RFD [2] as well as chain-like structure [3], which import the accelerating gaps into RFQ, were under investigation in Russia, USA and Japan. As the same reason, the Separated Function RFQ (SFRFQ) was proposed by the RFQ group of IHIP (Institute of Heavy Ion Physics) at Peking university [4], based on the experience of 26 MHz 1 MeV O$^+$ Integrated Split Ring (ISR) RFQ [5,6]. Generally the overall RFQ is divided into four sections: radial matching, shaping, gentle bunching and accelerating section according to the proposed design procedure [7]. The main idea of SFRFQ

is introducing gaps into RFQ by diaphragms, accelerating section will be partly or completely substituted by SFRFQ segment. So the structure can be used for a post-RFQ structure or a segment of RFQ. Initial results of electro-magnetic calculation and dynamics proved the possibility and higher RF efficiency of SFRFQ structure. A low-level rf model had been designed to test the structure technology.

SFRFQ STRUCTURE

The SFRFQ structure is shown schematically in Fig 1, where diaphragms are mounted onto the electrodes without surface modulation. Then every cell consists of a gap and a small quadrupole lense, the acceleration and focusing will not occur synchronously anymore.
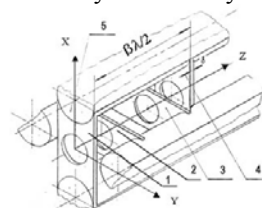

Figure 1: Schematic view of the SFRFQ.
(1,2,3&4 diaphragms, 5 RFQ electrode)

With static solver RELAX3D, equipotential distributions in SFRFQ have been determined. Fig 2 shows the equipotential lines at the longitudinal section.
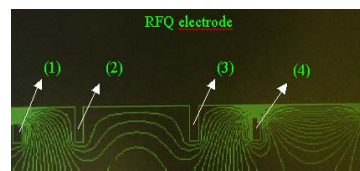

Figure 2: Longitudinal equipotential map at YOZ plane.

It is clearly displayed that accelerating electric fields occur in the gaps between diaphragms (1) and (2), (3) and (4) while electric focusing fields exist between (2) and (3), which were mounted on the same electrodes.
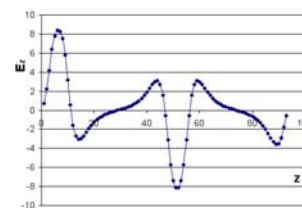

Figure 3: the electric field distribution along the axis.

Afterwards the electric field distribution on axis was determined and plotted in Fig 3. Besides accelerating fields, the reverse fields also were found between

diaphragms (2) and (3). As these diaphrams are at the same potential, so there are mainly quadrupole fileds off the axis except weak reverse field of higher multipole modes.
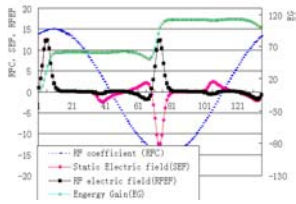

Figure 4: The theoretical axial field and energy gain.

The reverse field will decelerate beams and reduce the RF efficiency. To minish the decelerating field, a structure called asymmetrical $\beta\lambda/4$-long diaphragm SFRFQ was developed [8,9], where one side of the diaphragm pair is stretched to $\sim \beta\lambda/4$ so as to shield off more decelerating field. The calculated field distribution and the energy gain of the improved version are shown in Fig.4. The ions will be accelerated inside the gap of the diaphragm pair, and then drift freely in a distance of about $\beta\lambda/4$. 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.

In order to testify the simulation results and to investigate the structure technology of SFRFQ, a rf model had been designed, where the electrodes were excited by integrated split ring. The photo of the asymmetrical diaphragms is shown in Fig 5.
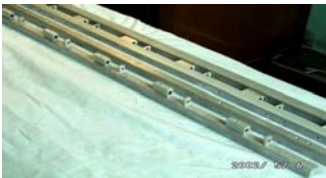

Figure 5: The electrodes with $\beta\lambda/4$-long diaphragms.

The electric field distribution E^2 along the axis was measured by bead pull measurement as the right part of Fig 6, there is a good agreement with the theoretical curve (the left part of Fig 6), which was modifed by considering the transverse focusing fields.
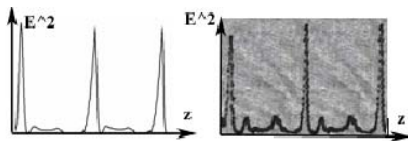

Figure 6: The calculated (left) & measured (right) axial field $E^2 \sim z$.

THE EQUIVALENT FOCUSING FACTOR OF SFRFQ

To compare the focusing power of SFRFQ with that of conventional RFQ, the equivalent focusing factor F should be determined. Actually, the phase advance σ_{t0} for SFRFQ can be readily obtained by writing down the matrix for the corresponding cell, assuming the synchronous phase is constant. On the other hand, for conventional RFQ, the focusing factor F is related to σ_{t0} as in the following:

$$\sigma_{t0}^2 = F^2 \frac{B_0^2}{8\pi^2} + \Delta_{rf} \qquad (1)$$

where $B_0 = \frac{qV}{mc^2}\frac{\lambda^2}{a^2}$, $\Delta_{rf} \propto \frac{\sin\phi_s}{\beta^2}$.

Hereby from formula (1), the equivalent focusing factor F of SFRFQ structure can be derived from phase advance σ_{t0} , providing both the synchronous phase ϕ_s and relative velocity β are constant.

OPTIMIZATION OF GEOMETRY FOR SFRFQ

The extra capacitance will be imported after installing a large number of diaphragms on the electrodes, which results in the fall of frequency and reducing the shunt impedance. Moreover, sparking may happen because of limited space between diaphragms and opposite electrodes. To study these problems, a rf model was simulated and optimized by MicroWave Studio (MWS) [10].

At first the RFQ electrodes excited by the split ring were simulated by MWS as Fig 7. Then diaphragms were mounted into the structure meanwhile enlarging only the distance between diaphragms and corresponding opposite electrodes, as shown in Fig 8. The parameters and some simulation results of both RFQ and SFRFQ structures were listed in table 1.
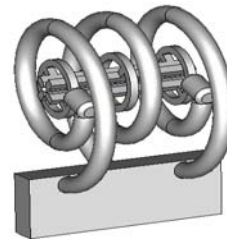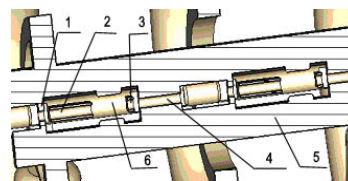

Figure 7: The RFQ model in MWS.

Figure 8: The SFRFQ electrodes after optimization. (1&3 thin diaphragms, 2&4 $\beta\lambda/4$-long diaphragms, 5 RFQ electrode, 6 quadrupole)

Table 1: The comparison between accelerating section in RFQ and SFRFQ

	accelerating section	SFRFQ
frequency (MHz)	25.4	24.1
Specific shunt impedance ρ (kΩ.m)	336	298
$\beta\lambda/2$ (mm)	68	68
Cavity length (m)	0.4	0.4
Z_{eff} $(\cos\varphi_s)^2$(φ_s=-25º) (MΩ/m)	13.3	31.0
Modulation	2	1
Quality factor Q_0	3393	3312
E_{pk} (MV/m)	10.8	12.9
Intervane voltage U(kV)	70	70
Kilpatrick ratio	1.51	1.8

Table 1 shows that although the specific shunt impedance ρ will be decreased 11% after installing diaphragms on electrodes, but the accelerating efficiency of gaps will be a great deal augmented. To consider both facors together, we introduce longitudinal effective impedance as in gap structures for RFQ. The ρ and Z_{eff} were respectively defined as (2) and (3):

$$\rho = U^2 \times l / P \qquad (2)$$

$$Z_{eff} = \frac{\left(\int |E_z(z)| dz\right)^2 T^2}{Pl} \qquad (3)$$

where P is power loss, l is the length of cavity and T is transit time factor.

It turned out the RF efficiency Z_{eff} $(\cos\varphi_s)^2$ in SFRFQ will be two times larger than in RFQ, meanwhile the maximum peak field in SFRFQ structure only goes up a little, which implies sparking will be not a problem for SFRFQ structure.

AN EXAPMLE OF DYNAMICS DESIGN

An example of dynamics design will be helpful to understand the advantages of the SFRFQ structure. Based on the dynamics of 26 MHz 1 MeV O$^+$ ISR RFQ [5,6], the O$^+$ beams were in succession accelerated from 1 MeV to 5 MeV by the SFRFQ. If the O$^+$ beams are accelerated only by the RFQ structure, more than 50 cells should be needed and the RFQ cavity will be 8 meters longer than the SFRFQ. The transmission will be nearly the same in the case of same aperture. Some parameters of both dynamics were listed in table 2.

Table 2: The comparison between both dynamics

	SFRFQ	RFQ
Beams	O$^+$	O$^+$
Frequency (MHz)	26	26
Injection energy (MeV)	1	1
Output energy (MeV)	5	5
Intervane voltage (kV)	70	70
Cell number	82	132
Average energy gain	48.8	30.3

per cell (keV)		
Synchronous phase	-25˚	-25˚
Modulation	1	2.04
Length (m)	10.3	18.5
Aperture (cm)	6.2	6.2
Transmission(5mA)	95.8%	96.0%

CONCLUSION

A new structure called SFRFQ was proposed in this paper. Considering the fact that drift tube structure is more efficient than RFQ, but it is not fit for very low energy range, we tried to utilize the accelerating gaps at the energy as low as possible meanwhile to keep the quadrupole electrodes for focusing. Initial results of electro-magnetic calculation and dynamics proved the possibility and higher RF efficiency of SFRFQ structure, so the total length of linac will be largely reduced if using SFRFQ structure as post-RFQ structure or substitution of accelerating section in RFQ.

ACKNOWLEDGEMENTS

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