INVESTIGATION ON DOUBLE DIPOLE FOUR-VANE RFQ STRUCTURE

Ki R. Shin[1], Yoon W. Kang, Aly E. Fathy[1], and Mark S. Champion
ORNL, Oak Ridge, TN 37831, [1]University of Tennessee, Knoxville, TN 37996, U. S. A.

Abstract

Four-vane RFQ is a general choice for the low energy injector of light ion accelerators. In this commonly used four-vane RFQ structure, each vane has undercuts at both ends to create open magnetic field paths that realize uniform electromagnetic fields along longitudinal direction. Meanwhile, there exists another undercut method called as double dipole (DD) that requires undercuts only on 2 vanes [1] that are interleaved with vanes with no undercut. The RFQ with DD cutback can provide a design option besides the traditional 4 vane cutback (4C) method. In this paper, we investigate and discuss some important DD RFQ features in detail: 1) Finite on-axis field at DD RFQ end section, 2) Dipole mode properties, and 3) Mode spectrum with respect to structure length. 3D simulation is utilized for this DD RFQ analysis.

INTRODUCTION

The radio frequency quadrupole (RFQ) has been widely used for focusing, bunching, and acceleration of ion particles [2]. The four-vane RFQ [3] with four vane cut-backs (4C) [2][4] is common design choice for light ion accelerator systems.

The four-vane RFQ is derived from the quadrupole ridge waveguide [3], and requires cut-backs on each vane ends. The cut-back is necessary to avoid perfect electric boundary condition on vane ends, which is essential to provide the required electric field uniformity in whole structure.

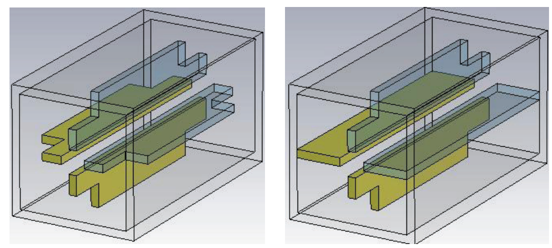
Researchers found that two other cut-back methods are possible to maintain the uniform quadrupole mode: double dipole (DD) and folded dipole (FD) [1][5]. These schemes were used in a < 2.0 λ length structure demonstration RFQ model at Chalk River. One drawback of the DD and FD structures is the generation of finite on-axis field at RFQ ends in quadrupole mode. However, these problems may be relieved by adjusting ion source energy level and RFQ radial matching section design [8].

The DD structure is of special interest in this paper because of its unique characteristics on dipole mode that leads to different mode spectrum results. This may provide an alternative design option in some cases where 4C RFQ mode separation is very small.

Therefore in this paper, we investigate some important features of DD RFQ. First, we discuss the on-axis voltage generation in DD RFQ. Next, some interesting dipole mode properties in DD RFQ are covered with qualitative description and discussion. Finally, a DD RFQ mode spectrum result with the Spallation Neutron Source (SNS) RFQ geometry is presented as an example case. The 3D simulation tool CST Microwave Studio [6] is utilized in this study.

ON-AXIS FIELD AT DD RFQ ENDS

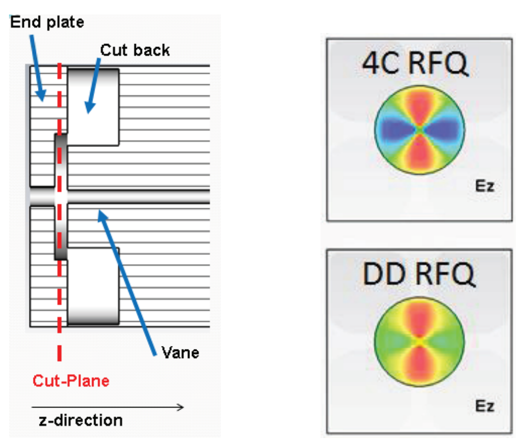
Fig. 1 shows a perspective view of 4C and DD RFQ cut-back geometries. In conventional 4C RFQ, all four vanes are not electrically touching the both end-plates. Meanwhile, only two opposing vanes make contacts to the end-plate in DD RFQ.



(a) (b)

Figure 1: RFQ cut-back - (a) 4C, (b) DD.

Because of this electrical contact of two vanes, DD RFQ generates a finite on-axis voltage. Fig. 2 describes how the on-axis voltage in z-direction is created. In 4C RFQ, the sum of Ez field on beam axis becomes zero. Each RFQ vane induces RF voltage of π phase difference from the adjacent vanes; hence cancellation of on-axis voltage occurs in 4C RFQ [7]. The short circuit condition of two vanes in DD RFQ, however, diminishes this cancellation and finite on-axis potential remains.



(a) (b)

Figure 2: RFQ end region - (a) geometry, (b) Ez field.

The existence of a finite on-axis voltage requires a different end-region design scheme as shown in Fig. 3. The conventional design for 4C RFQ in Fig. 3 (a) is not optimized to reduce the axial voltage. Previous work [1] suggested the design in Fig. 3 (b) which can decrease this axial voltage the most, however it may induce gas flow issue due to large bore. An intermediate design between these two is the conical one shown in Fig. 3 (c). This design has advantages of small bore with reduced axial voltage.

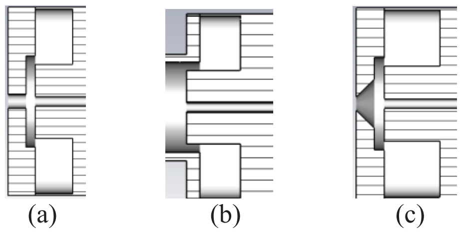


Figure 3: Plate geometry - (a) closed (b) open (c) conical.

The results of simulated axial voltage are summarized in Table 1. The SNS RFQ body geometry with 5λ length is utilized in this simulation study. The 550 kW peak power is assumed to have a similar operating condition in the SNS RFQ. The simulated axial voltage with conical end-plate geometry is 6.38 kV, about 9.8% of SNS RFQ 65kV input beam energy. This axial voltage can be further decreased by introducing a radial matching section (RMS) [8] in RFQ inlet. In this example with SNS RFQ RMS design, 4.77kV axial voltage, about 7.4% of the input beam energy, could be observed.

Table 1: On-Axis Voltage Results by Plate Geometry

	On-axis voltage	*Ratio / 65 kV*
Closed	9.87 kV	15.2 %
Open	3.75 kV	5.8 %
Conical	6.38 kV	9.8 %
Conical + RMS	4.77 kV	7.4 %

DIPOLE MODE CHARACTERISTICS

The DD RFQ provides a unique mode spectrum because of different cavity coupling and dipole mode boundary condition from 4C RFQ.

Figs.4 show how the quadrupole and dipole modes are generated in 4C RFQs. The RFQ magnetic field line path should be closed through circulation in cut-back areas [9]. When the magnetic field in two diagonal quadrants have the same polarity, it becomes the quadrupole mode. Otherwise, it becomes a dipole mode.

In azimuthal plane, the 4C RFQ fundamental quadrupole and dipole modes have π and π/2 phase difference per each quadrant, respectively. For a short RFQ, the magnetic coupling through end-region is stronger than the electric coupling via vane gaps. Hence, the fundamental quadrupole frequency with π phase difference becomes lower than the fundamental dipole frequency with π/2 phase difference [10]. For a long RFQ, however, the electric coupling dominates and the fundamental quadrupole frequency has higher value than the fundamental dipole frequency.

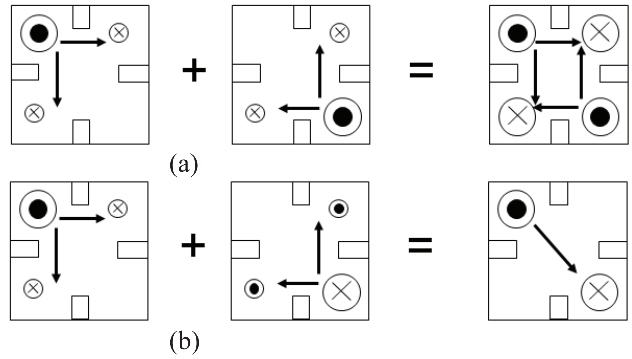


Figure 4: H field circulation at 4C RFQ end-region - (a) quadrupole, (b) dipole mode.

On the other hand, the DD RFQ modes are generated by electrically coupled two dipole cavities. Likewise 4C RFQ, the RF phase difference of each set determines the quadrupole and dipole modes. When two dipoles have 0 or π phase difference, it becomes the dipole or quadrupole mode. Since the two dipoles are connected only through electric coupling, the fundamental quadrupole frequency with π phase difference is always higher than the fundamental dipole frequency with open boundary in Fig. 5 (b). Therefore, the tuning method can be always kept same in DD RFQ independent to the structure length.

The vane pair short circuited to end-plates shown as red box in Fig. 5 causes the DD dipole modes not to degenerate as 4C RFQ dipoles. The DD modes are formed by combination of two dipoles, and the horizontal and vertical dipoles do not have same boundary condition because of the end-plate. H field in one dipole (Fig. 5 (b)) circulates through cut-back area that can be considered as an open boundary. Meanwhile, the other dipole in Fig. 5 (c) experiences the short circuit boundary. The magnetic field path is closed through the small bore openings in this short dipole.

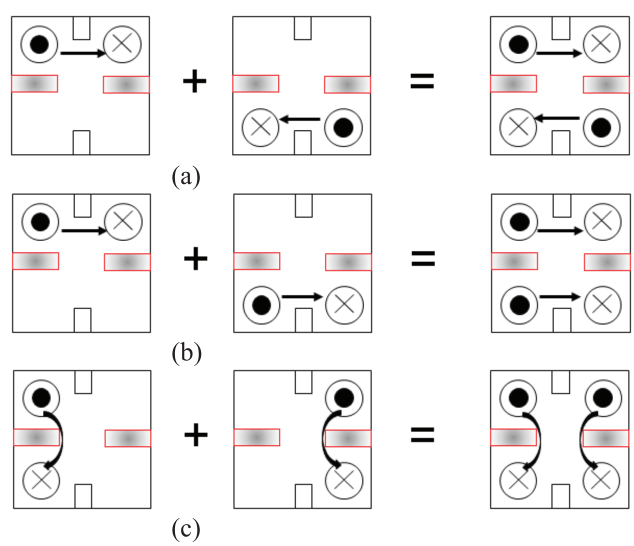


Figure 5: H field circulation at DD RFQ end-region- (a) quadrupole, (b) dipole (open), (c) dipole (short) mode.

ISBN 978-3-95450-138-0

Although two dipole modes are not degenerate in DD RFQ, the entire mode spectrum is not complex. Since the open and short circuit boundary dipoles can be approximated as the waveguide and cavity modes, those can be related by cavity length l_v as (1) [11]. The frequency of short fundamental dipole $f_{TE(S)}$ is similar to the first harmonic frequency of the open fundamental dipole $f_{TE(O)}$ and so on. Their harmonic frequencies have similar relations as well.

$$f_{TE(S)} \cong \frac{c}{2\pi}\sqrt{\left(\frac{2\pi}{c}\cdot f_{TE(O)}\right)^2 + \left(\frac{\pi}{l_v}\right)^2} \qquad (1)$$

MODE SPECTRUM BY RFQ LENGTH

Figs. 6-7 show the simulation results of 4C and DD RFQ mode spectrum with structure length. The SNS RFQ transverse geometry is used in this simulation. DD dipole frequencies are different from 4C ones, hence DD RFQ could be an alternate design option in some structure lengths. The open boundary dipole in DD RFQ (TE01n+1) has similar frequency with the short dipole (TE10n) by a harmonic order difference. The fundamental open dipole frequency TE010 is always lower than the fundamental quadrupole frequency TE110. With SNS geometry, DD RFQ has good mode separation around 3λ, 5λ, and < 1.5λ lengths.

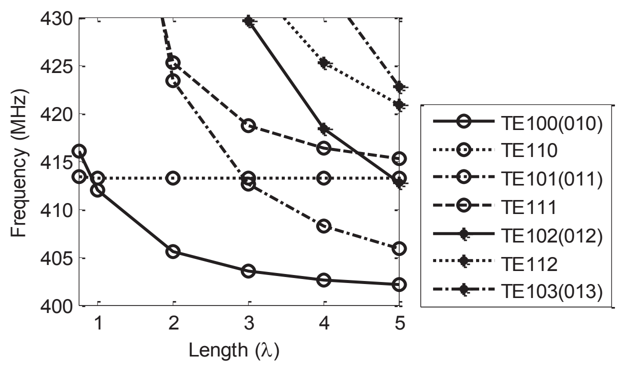


Figure 6: Mode spectrum results of 4C RFQ.

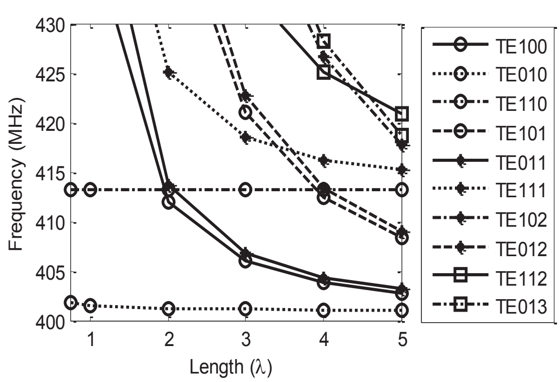


Figure 7: Mode spectrum results of DD RFQ.

CONCLUSIONS

Some results of investigation on the properties of DD RFQ are discussed. The on-axis field generation and end-region design examples are presented. An end gap axial voltage of 4.77 kV is expected with 550 kW peak power. Dipole mode properties of DD RFQ are compared with the 4C RFQ with qualitative discussion. Although dipole modes do not degenerate in DD RFQ, overall mode spectrum is still shows their harmonic relation. The simulation results of mode spectrum are in good agreement with expectation from qualitative approach. The DD RFQ can be an alternative design option in some RFQ lengths where it provides better mode separation than 4C RFQ.

ACKNOWLEDGMENT

This work was supported by SNS through UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. DOE. The Authors thank the Basic Energy Sciences program of the U.S. DOE and the Research Accelerator Division of SNS for supporting this work.

REFERENCES

[1] R. Hutcheon et.al., "RFQ linac structure development at CRNL", IEEE Trans. on Nuc. Sci. Vol. NS-30, No. 4, Aug. 1983.

[2] I.M. Kapchinskiy and V.A. Tepliakov, Prib. Tekh. Eksp. 2, 19-22 (1970) & 4, 17-19 (1970).

[3] L. Young, "25 years of technical advances in RFQ accelerators," Proceedings of 2003 particle accelerator conference, Portland, OR.

[4] M. Browman et. al., "Studying the end regions of RFQs using the MAFIA codes", Proceedings of 1988 linear accelerator conference, Williamsburg, VA.

[5] R.M. Hutcheon et. al., "100% duty factor RFQ linac systems at CRNL," IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983.

[6] CST Microwave Studio, www.cst.com

[7] P. Balleyguier et. al., "Simulations vs. measurements on IPHI RFQ cold model," Proceedings of 2002 European Particle Accelerator Conference, France.

[8] K. Crandall et. al., "RF quadrupole beam dynamics design studies," Proc. 10th Linear Accelerator Conf. Montauk, NY, 1979.

[9] T. Wangler, "RF linear accelerators," 2nd edition, Weinheim, Germany: Wiley, 2008.

[10] P. Lapostolle, A. Septier, "Linear accelerators," North-Holland Publishing Company, Amsterdam, 1970.

[11] R. Collin, "Foundations for microwave engineering, "second edition, IEEE press series on electromagnetic wave theory, 1992.