Nuclear Inst. and Methods in Physics Research, A 886 (2018) 119–124

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Quadrupolar asymmetry in shifted-stem vane-shaped-rod radio frequency quadrupole accelerator

Nitin Mehrotra *

Nuclear Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085, India
Homi Bhabha National Institute, Anushaktinagar, Mumbai 400 094, India

A R T I C L E   I N F O

Keywords:
Quadrupolar asymmetry
Dipole effect
Rod-type RFQ
Shifted-stem RFQ

A B S T R A C T

Quadrupolar Asymmetry (QA), which has been a rampant problem for rod-type Radio Frequency Quadrupole (RFQ) Linacs, arises due to the geometry of resonant structure. A systematic parametric simulation study has been performed to unravel their effect on Figure of Merit (FoM) quantities namely Quality Factor (Q), Shunt Impedance (R_{sh}) and Quadrupolar Asymmetry (QA). A novel stem and cavity shape is proposed, which caters to the profile of electromagnetic fields of the resonant structure. A design methodology is formulated, which demonstrates that Quadrupolar Asymmetry can be annihilated, and a symmetric electric field can be produced in all four quadrants of rod-type RFQ accelerator.

1. Introduction

Various resonant structure designs have been used for the Radio Frequency Quadrupole (RFQ) Linear Accelerator with frequency ranging from 10 MHz [1] to 473 MHz [2]. For light ions like proton, a higher frequency (>300 MHz) [3] is preferred and vane type RF structures [4] are common. Noticeably, the frequency frontier has been notched higher with the construction of a 750 MHz pulsed four-vane proton RFQ at CERN [5]. For heavy ions ($m/q \geq 4$), a lower frequency (<150 MHz) [6] is preferred and rod-type [7], split-ring [8], spiral [9], split-coaxial [10], vane type with windows [11,12], 90°-apart-stem [13], Ladder [14,15] and IH [16] kind of RF structures have been designed. With technological advances, the demarcation of frequency between light and heavy ions is getting blurred and numerous cross-references can be found easily. The power density on rod shaped electrodes [17] is very high and cooling rod shaped electrodes of RFQ is challenging. Hence vane shaped electrodes [18] have replaced the rod shaped electrodes, also allowing better mechanical stability for CW (Continuous-Wave) operation. Near the beam axis, the four vane shaped electrodes form quadrupole, which either preserve orthogonality (90° inter-electrode angle) [see Fig. 1(b)] throughout transverse cross-section or become parallel after certain distance [see Fig. 1(a)]. The OrthoPar (Orthogonal-Parallel) type vane electrodes are joined by stems, whose base form a rectangle between adjacent opposite stems [see Fig. 2(a)]. Also, the adjacent opposite stems project completely on each other. This is the traditional rod-type RFQ structure pioneered by A. Schempp at IAP, Germany [7]. The orthogonality preserving vane shaped electrodes are joined by stems, whose base form a parallelogram, among adjacent opposite stems [see Fig. 2(b)]. This modified-stem vane-shaped-rod RFQ structure had been developed by H. Fujisawa at Kyoto University, Japan [18].

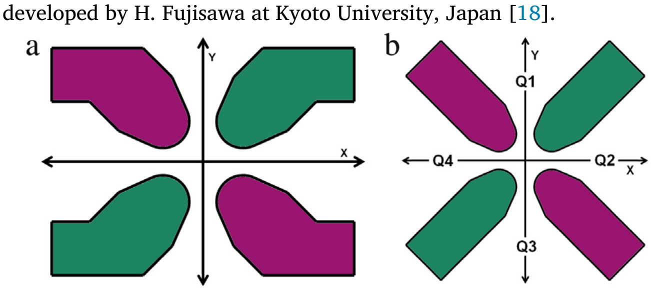

Fig. 1. Quadrupole shapes for vane-shaped-rod RFQ (a) OrthoPar type vanes (b) Orthogonal type vanes with designated four quadrants.

The rod type RFQ is a modular structure where resonant unit RF cells are added in series to generate full length of RFQ. The rod type RFQ consists of Normal RF cells and End RF Cells. The normal RF cell is coupled inductively to other RF cells on either side. The Unit RF Cell consists of four vane electrodes, assembled in quadrupolar symmetry, held by two stems above the base plate. Each stem holds two vanes, which are at same potential. The vanes act as Capacitors (C) and stems act as Inductors (L), thus forming the LC resonant circuit [see Fig. 2(d)].

* Correspondence to: Bhabha Atomic Research Centre, Trombay, Mumbai—400 085, India.
E-mail address: mehrotra@tifr.res.in.

https://doi.org/10.1016/j.nima.2017.12.075
Received 30 September 2017; Received in revised form 6 December 2017; Accepted 26 December 2017
Available online 29 December 2017
0168-9002/

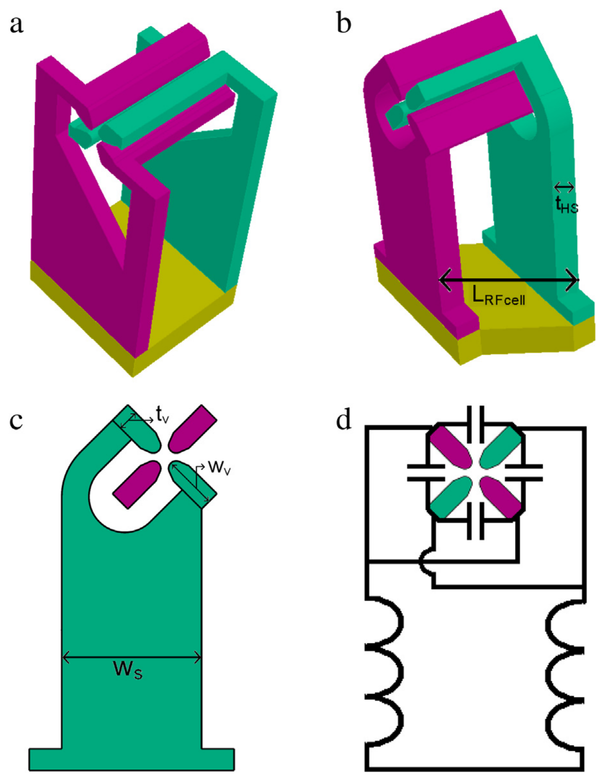

Fig. 2. (a) Traditional rod-type RFQ model (b) Modified-stem vane-shaped-rod RFQ model showing unit RF cell Length (L_{RFcell}) and half stem thickness (t_{HS}) (c) Transverse cross-section view of modified-stem holding two vanes. Also shown is the stem width (w_s), vane width (w_v) and vane thickness (t_v) (d) Equivalent lumped circuit for rod-type RFQ.

The resonant structure consisting of vanes, stems and base-plate is enclosed in a vacuum chamber of cylindrical or rectangular shape. Unit RF Cell Length [see Fig. 2(b)] is defined as the centre-to-centre distance between adjacent opposite stems holding the four vanes. The rod type RFQ structure where the stems can be modelled as parallel plate transmission line and vane-shaped-rods as two-wire transmission line is excited in transverse π and axial 0 mode [7]. With respect to ground, a pair of adjacent stems always bears opposite polarity, giving rise to $\lambda/2$-rod-RFQ nomenclature. The rod RFQ with equidistant stems gives higher shunt impedance [19].

In this paper, a parametric simulation procedure for modified-stem vane-shaped-rod RFQ, with emphasis on minimizing quadrupolar asymmetry, is enunciated. In Section 2, a description of quadrupolar asymmetry for two kind of rod-type RFQ is given. In Section 3, the simulation strategy and effect on various figure of merit quantities is discussed. Therein, shifted-stem and HUT shaped cavity geometry is proposed. In Section 4, brief outlook is stated.

2. Quadrupolar asymmetry

The rod-type RFQ in general suffers from two problems (i) Quadrupolar Asymmetry (QA) (ii) Longitudinal Electric Field flatness. The Quadrupolar Asymmetry (QA) in rod type RFQ arise due to different potential on the four vane shaped electrodes. The difference in height of lower and upper vane shaped electrodes cause difference in the inductivity of the two arms of stem resulting in unequal charge transfer and thereby Quadrupolar Asymmetry (QA). Each stem of rod type RFQ behaves as a $\lambda/4$ transmission line, thereby voltage increases linearly with height. This voltage difference acts as a steering force and shifts the beam axis lower in the vertical direction. Historically, it is called dipole effect [20]. Quadrupolar Asymmetry (QA), which has detrimental effect on beam transmission and emittance, needs to be minimized for stable operation of rod-type RFQ at full power.

Quadrupolar Asymmetry (QA) has been a topic of continued and varied research for RFQ designers around the world. The problem of longitudinal electric field flatness manifests itself along the full length of RFQ and is a function of longitudinal co-ordinate. Hence, to evaluate and demystify it, full-length simulations are required. However, QA is independent of the total RFQ length and can be decoded using unit RF cell methodology. Among the various kind of resonant structures for rod-type RFQ, two structures which stand out in ease of fabrication, assembly and alignment are the traditional rod-type RFQ and the modified-stem vane-shaped-rod RFQ. As described in the following sections, a differentiation between the two kind of rod RFQ structures is vital as it leads to different class of QA and its method of solution.

2.1. Traditional rod-type RFQ

Various approaches have been utilized for mitigating the menace of Quadrupolar Asymmetry (QA) in rod-type RFQ's. One of the approaches involves shaping the middle portion of stem with an angle [see Fig. 2(a)] to control QA within ±1% in electric field [20]. For the RFQ in Ref. [21], QA of 12% in voltage was reduced to 5% by shaping the centre slope of stem. Moreover, the steepness of centre slope is limited by the tuning plate height which itself affects the QA in such RFQs. In another approach used for the 80.5 MHz RFQ [22], QA ∼ ±2%–3% in electric field is achieved by providing a slope both at the centre and at the side of stem together with shorter vane width. With the advent of new design procedures for cw applications, the 53.67 MHz RFQ in Ref. [23] reports QA ∼ 8%–9% in voltage. Another design of rod-type RFQ at high frequency has indicated that QA can be compensated and even over compensated [24]. It is worthwhile to state that one of the finest cw performing RFQ is the 37 MHz split-ring heavy ion RFQ at TRIUMF, which has QA of ±1% [8].

2.2. Modified-stem vane-shaped-rod RFQ

For the modified-stem vane-shaped-rod type RFQ, the Quadrupolar Asymmetry (QA) is higher than traditional rod-type RFQ primarily due to larger vane widths. The 33.3 MHz RFQ built at Kyoto University [18] had QA ∼ ±6% in electric field and the 35 MHz RFQ at VECC [25] had QA ∼ ±8% in electric field. Measurements on the three RF cell prototype of 75 MHz modified-stem vane-shaped-rod RFQ structure [see Fig. 3(a)], which has been developed at BARC-TIFR PLF showed ±14% QA in electric field [26]. Fig. 3(b) shows the simulated electric field profile at centre of unit RF cell along the horizontal (EmodX) and vertical (EmodY) direction. It is to be observed that QA scales linearly with frequency for a specified vane-stem geometry. In yet another approach, the VECC group adapted stem shape with centre as well as side slope and relocated lower vane holding position to upper side to achieve ±3% QA in electric field for the 80 MHz rod-type proton RFQ [27].

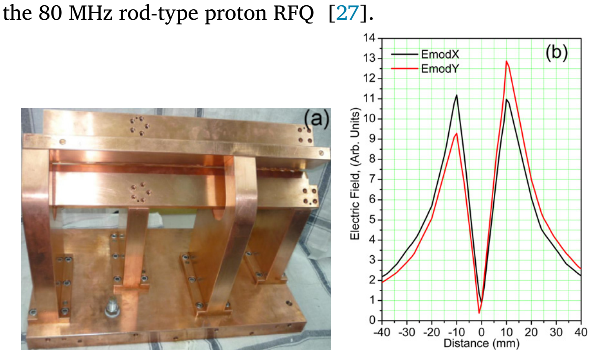

Fig. 3. (a) Three RF cell prototype of 75 MHz modified-stem vane-shaped-rod RFQ (b) plot of simulated electric field along the transverse X and Y direction.