R&D ON EFFICIENT ULTRA-HIGH FREQUENCY RFQ STRUCTURES

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Abstract

RFQ (radio-frequency quadrupole) accelerating structures for frequencies below 400 MHz have been extensively investigated for decades. To realize modern medical accelerators with more compact layouts, there is growing interest in using ultra-high frequencies (UHF: 0.3–3 GHz). At high frequencies, 4-vane RFQs tend to surpass 4-rod RFQs in terms of efficiency and beam parameters. However, 4-rod RFQs offer lower cost per meter, reduced mechanical complexity, and a simpler tuning process, making them particularly attractive for low-cost applications. This study presents R&D toward efficient UHF 4-rod RFQ structures, with a focus on dipole effect mitigation.

THEORY

Dipole field effects are an intrinsic problem that degrades the performance of 4-rod RFQ accelerators due to the asymmetry of their internal structures. Various techniques have been developed to mitigate these effects by balancing the length differences of the current paths from the ground plate to the electrodes at different heights. Solutions that modify the stem geometry in the plane perpendicular to the beam axis (xy-plane) are common practice and have been extensively studied [1]. A new technique has been developed that modifies the stem geometry along the beam axis (longitudinally in yz-plane), called “bending the lower-electrode supporters along the accelerating channel” (BLESAC) [2]. Additionally, a new modified perpendicular compensation technique was developed, based on an already available design [1]. This new technique uses a lateral displacement and widening of the stem cut, while also shifting the outer border of the arm to the upper electrodes by the same amount. Advantages of this new method are:

- equal width of all stems—no width differences for even-odd stems. Therefore, tuner plates can employ the full width of the structure.
- Higher mechanical stability of the upper electrodes—lower vibration susceptibility.
- More space for water cooling channels—especially useful when used in combination with additive manufacturing [2].
- Possibility of lower parasitic inductance of the upper electrode stem arms—higher reluctance due to increased magnetic path lengths and therefore lower dipole field effects (this has not yet been confirmed).

Dipole field effects in 4-rod RFQs are detrimental because they introduce an unwanted transverse field component that displaces/focuses the beam from its ideal central axis. This leads to beam deflection, reduces the effective aperture, and thereby lowers the transmission efficiency. In addition, the dipole field can deteriorate the symmetry of the focusing forces (see Fig. 1).

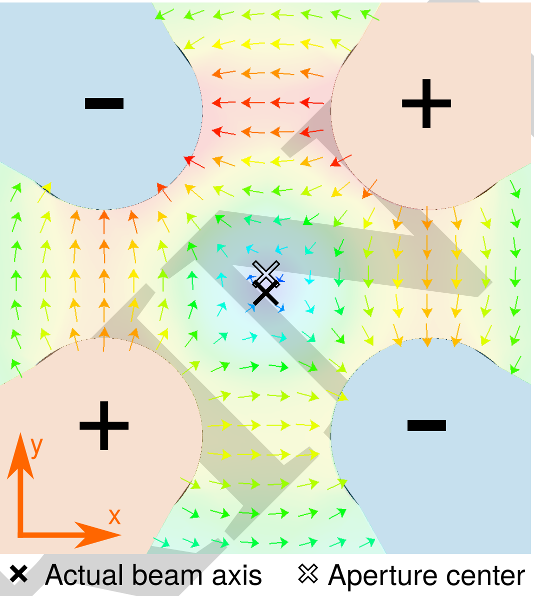

Figure 1: Strongly deflected beam axis by an unwanted dipole field.

The dipole factor D of a 4-rod RFQ arises from the different heights $\sim L$ of the electrodes above the ground plate. This creates two current paths of unequal length, resulting in different inter-rod voltages. Equivalently—considering that upper and lower electrodes form part of the same resonating structure— the upper electrodes are slightly farther from the resonator’s feeding point (the ground plane). Therefore, the resonator’s standing wave produces a slightly higher voltage at the upper electrodes (see Fig. 2). The dipole factor D is defined as follows:

$$D \equiv 1 + \frac{V_{uir} - V_{lir}}{V_{lir}}\,, \tag{1}$$

where V_{uir} is the upper inter-rod voltage and V_{lir} is the lower inter-rod voltage. For this study, the specific shunt impedance R_p is defined as follows:

$$R_p = \frac{V^2}{P/l}\,, \tag{2}$$

where V is the average inter-electrode (inter-rod) voltage, and P is the RF power loss within the resonator, and l is the

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resonator length—the internal length from lid to lid of the cavity. Voltage flatness $\Delta V/V$ is defined as follows:

$$\Delta V/V[\%] = 100 \cdot \frac{\max V(z) - \min V(z)}{\frac{1}{L}\int_0^L V(z)\,dz}, \qquad (3)$$

where L denotes the length of the structure used for the flatness calculation, i.e. the distance from the midpoint of the first stem to the midpoint of the last stem in the direction of z.

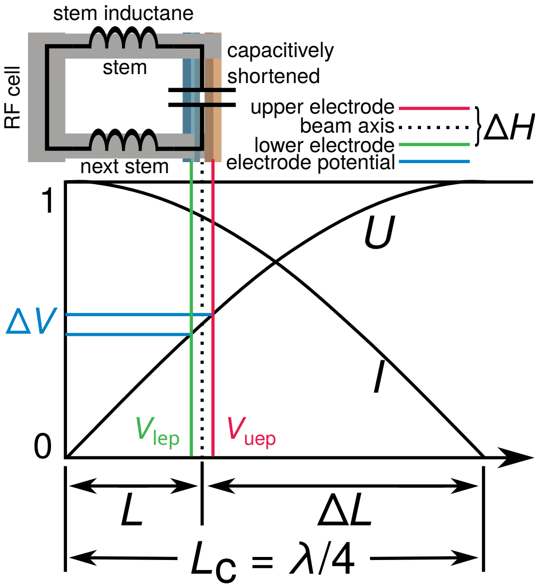

Figure 2: Principle of a capacitively loaded $\lambda/4$ transmission line resonator.

The greater heights/lengths of the upper electrode supporting arms introduce an additional parasitic inductance L_A—in contrast to the lower electrode arms (see Fig. 3). This asymmetry can be compensated by artificially increasing the inductance of the lower electrode arms.

Various methods may be employed to compensate for the parasitic inductance L_A (see Fig. 4). This can be achieved either by:

- increasing the inductance of the lower electrode arms—for example, by extending their effective length through perpendicular displacement—or
- reducing the inductance of the upper electrode arms—for example, by increasing material thickness to reduce cross-section.

RESULTS

The following results show three test cases for the discussed methods (see Table 1). Two test cases at 325 MHz: one test case with perpendicular dipole compensation and one test case with a mixed perpendicular and longitudinal BLESAC compensation (see Fig. 5), where B stands for BLESAC and P for Perpendicular. Additionally, one test case for perpendicular compensation at 433 MHz is presented. It should be mentioned, that all used models use angular inner cutting— with varying cutting angles. Therefore, the dipole fields have been partly compensated by this classic method and not only by the presented methods.

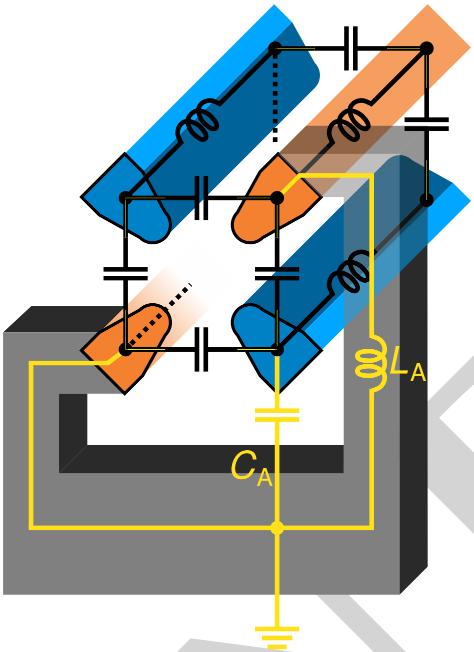

Figure 3: Equivalent circuit model of a single stem and electrodes. Showing the parasitic inductance L_A.

Table 1: Comparison of Cavity Parameters of the Three Reviewed Test Cases

Parameter	**325 MHz B+P**	**325 MHz P**	**433 MHz P**
Q	5704	5951	4868
f [MHz]	324.69	325.19	434.01
D	1.002	1.000	1.017
R_p [kΩm]	55	56	35
$\Delta V/V$ [%]	10.1	8.8	14.9

Both 325 MHz versions show very similar results with a slight drop off of the Q-factor (-4.1 %) and slightly reduced voltage flatness (+1.3 % points) between the BLESAC and the perpendicular version. Between 433 MHz and 325 MHz we see reduced performance in Q-factor (-18.2 %), shunt impedance (-37.5 %) and reduced voltage flatness (-6.1 % points). Considering the frequency dependant empirical scaling factors for normal conducting resonator structures [2], the observed values seem to be in a reasonable limit. Reduction in voltage flatness can be mainly attributed to end-field enhancement at the boundaries of the electrodes (see Fig. 6), which can probably partly compensation through further optimization.

All three test cases show nearly optimal dipole factor D. Where both 325 MHz versions show undercompensation in the per mill range. The 433 MHz case shows slightly stronger undercompensation with 1.7 %. Figure 7 shows $D(z)$ over the length of the structure. As shown, all three lines stay within a narrow band of roughly ±2.5 % around their average.

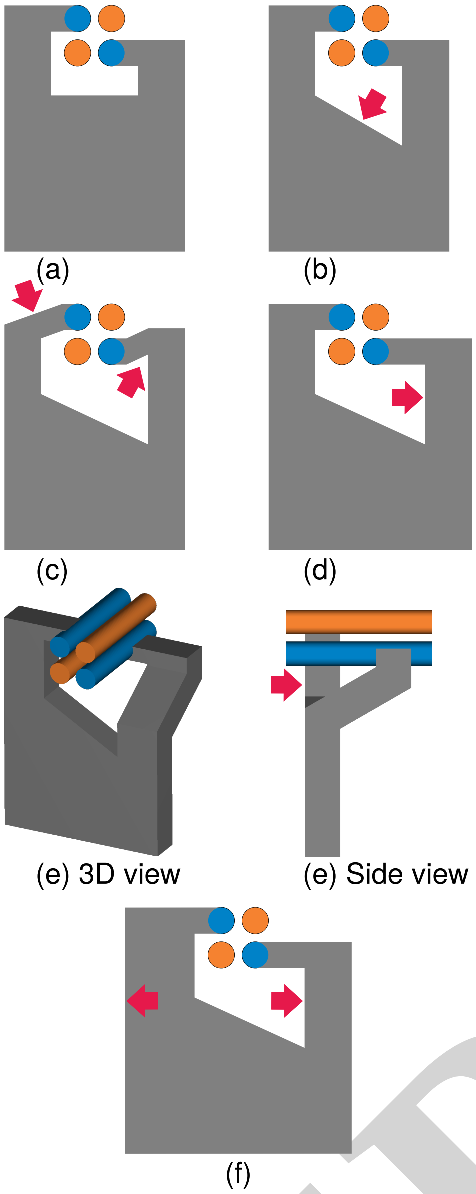

Figure 4: Overview of dipole effect mitigation methods for 4-rod RFQs as shown in [3]: (a) Stem without dipole optimization. (b) Stem cutting, classic dipole optimization [4]. (c) Current path adjustment, perpendicular to accelerating channel [5]. (d) Lower arm displacement, perpendicular to accelerating channel [1]. (e) Current path length adjustment along accelerating channel (BLESAC) [6]. (f) A modified version of d as used in this paper. Resulting in a constant width RFQ structure.

CONCLUSION

Simulations demonstrate promising results for modified 4-rod RFQs operating above 325 MHz. Full dipole mode compensation can be achieved across the entire structure while maintaining performance comparable to existing RFQ designs at this frequency [7]. However, the voltage flatness could be further improved through end-field optimization.

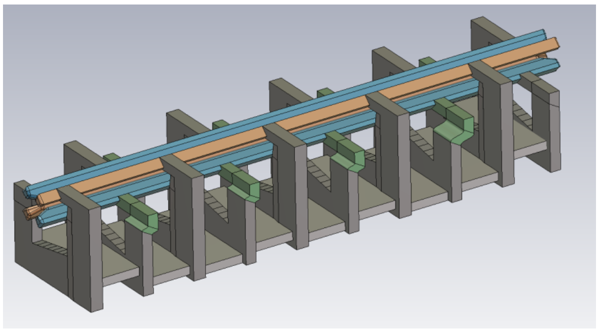

Figure 5: A 325 MHz 4-rod RFQ with widening of the stems inner cutting—perpendicular compensation. And longitudinal dipole compensation ”BLESAC” (in green). Cavity and ground plate are not displayed for clarity.

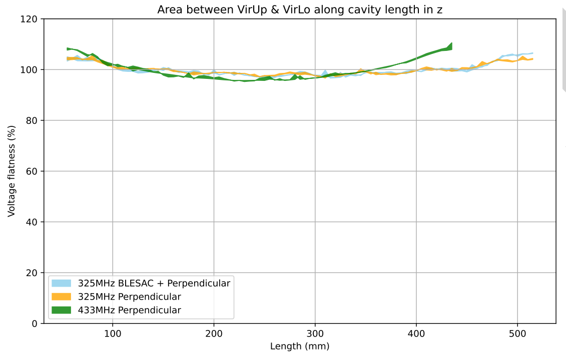

Figure 6: Simulation results of the three reviewed test cases. Shown is the voltage flatness of the upper and lower inter-rod voltage along the length of the cavity.

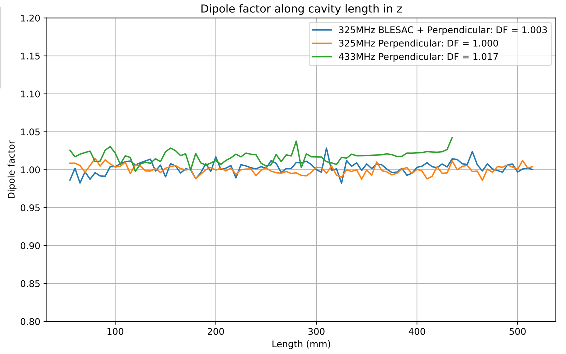

Figure 7: Simulation results of the three reviewed test cases. Shown is the dipole factor along the length of the cavity.

ACKNOWLEDGMENTS

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