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NEW METHOD FOR OVERCOMING DIPOLE EFFECTS OF 4-ROD RFQs

S. Wunderlich*, C. Zhang, GSI, Darmstadt, Germany

Abstract

A new-type stem has been developed and simulated for 4-rod RFQs. Different than the conventional stem, its two electrode holders have different longitudinal positions (in the beam direction) in order to balance the difference in length of the current paths from the ground plate to the upper and lower electrodes. The dipole effect at different settings for the longitudinal positions of the electrode holders were examined and will be discussed.

INTRODUCTION

The asymmetrical structure of 4-rod RFQs will cause dipole modes. Which can have a negative impact on the design beam performance.

As shown in Fig. 1 a 4-rod RFQ can be described by a chain of capacitively shortened $\lambda/4$ resonators. Like for any quarter wave structure, there is a voltage gradient along the height of the stem structure, which leads to higher potential on the upper electrodes (see also Fig. 1) [1]. This is the origin of the dipole effect for 4-rod RFQs.

To compensate this effect the current path lengths of the two stems must be balanced. The classical way to compensate the dipole field is to make an inner cutting on the stem (see Fig. 2). Various new methods to compensate dipole field components have been proposed, which use path deviations or alternating stem displacements perpendicular to the beam axis [2]. Inner cuttings can be used to provide more space for magnetic field that can evolve to increase charge transport to the undersupplied lower electrodes [3].

In this paper, a new idea to modify the electrode holder of the arm to the lower electrodes based on the classic method is being proposed. It prolongs the current path to the lower electrodes by shifting the electrode holder in longitudinal direction by Δz.

Figures 2 to 3 are showing the basic concepts of a model with newly developed stems. Intensive simulations with CST Studio Suite [4] have been performed on the new model with different settings for Δz as well as the rotating angle α of the top part of the arm (see Fig. 3).

MODEL DEVELOPMENT

An existing 4-rod RFQ model with inner cutting was used as a starting point to create the new model. The main parameters of the existing model are shown in Table 1, with a design frequency of 197.5 MHz. Added was the possibility to shift the electrode holder of the arm to the lower electrodes by an arbitrary value. Additionally α—connecting the fixed part of the arm to the lower electrodes to the electrode holder—can be freely chosen (see Fig. 3).

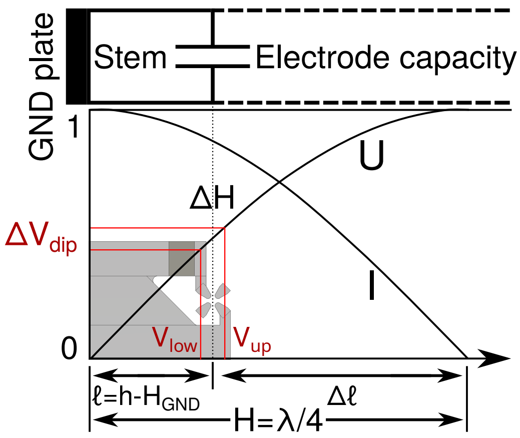

Figure 1: Potential distribution along the height of the stem. Showing the voltage difference between the upper and lower electrode pair [1].

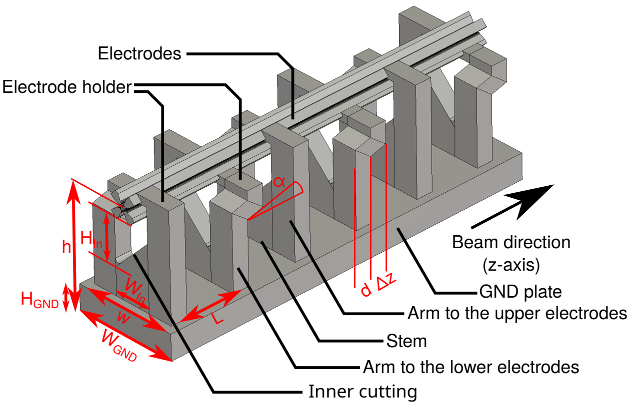

Figure 2: New type 4-rod RFQ model. This particular model uses a $\Delta z = 20$ mm with $\alpha = 15°$.

Table 1: Main Geometric Parameters

Name	**Value**	**Description**
Average aperture	3.6980 mm	a (radius)
Electrode radius	2.7735 mm	e
Stem width	106 mm	w
Inner cutting ang.	45°	β
Inner width	44.107 mm	W_{In}
Inner height	44.666 mm	H_{In}
Stem thickness	20 mm	d
Stem z-spacing	80 mm	L (center to center)
GND plate height	30 mm	H_{GND}
GND plate width	126 mm	W_{GND}
Beam axis height	142 mm	h (incl. GND plate)
Cavity radius	140 mm	incl. GND plate
Rotating angle	0°, 15°, 30°	α
Electrode holder shift	0 to 40 mm	Δz (in 10 mm steps)

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* S.Wunderlich@gsi.de

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SIMULATION

Analysis

In the ideal case, the voltage between the upper electrode pair V_u and the lower electrode pair V_l is the same, but with inverted polarity (see Fig. 4). The dipole mode perturbs this equality, increasing one of the voltages and decreasing the other by means of superposition. The strength of this perturbation effect can be expressed by the dipole factor DF with the following definition:

$$DF = 1 + \frac{V_u - V_l}{V_l}, \tag{1}$$

where V_u and V_l are the absolute values of the voltages between the upper and lower electrode pairs, respectively. Depending on which of the voltages is greater, DF will be greater, equal or less than 1. A value greater than one ($DF > 1$) means that the current path of the short stem is shorter than the current path of the long stem—the system is undercompensated. Accordingly, a value less than one ($DF < 1$) means that the short stem current path is too long—the system is overcompensated.

The dipole factor is an important parameter for RFQ designs, but it is not the only figure of merit. The specific shunt impedance R_p, the resonant frequency f_0 (fundamental eigenmode) and the Q-factor have been also checked.

The specific shunt impedance R_p describes the RF power losses of the resonator structure and is defined as follow:

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

where V is the effective inter-rod voltage averaged over the resonator chamber length l and P is the power loss within the resonator chamber.

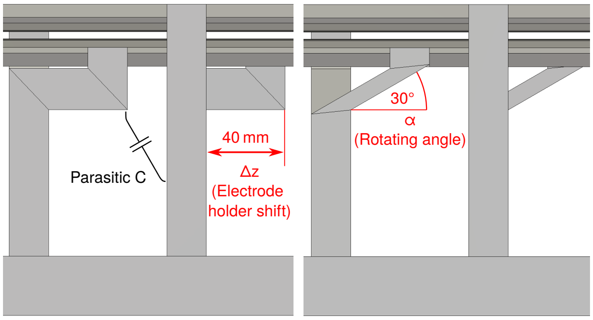

Figure 3: Side view of two variants of the model. Both variants use $\Delta z = 40$ mm with $\alpha = 0^\circ$ *and* 30°. Additionally depicted is the parasitic capacitance between one stem and the following stem.

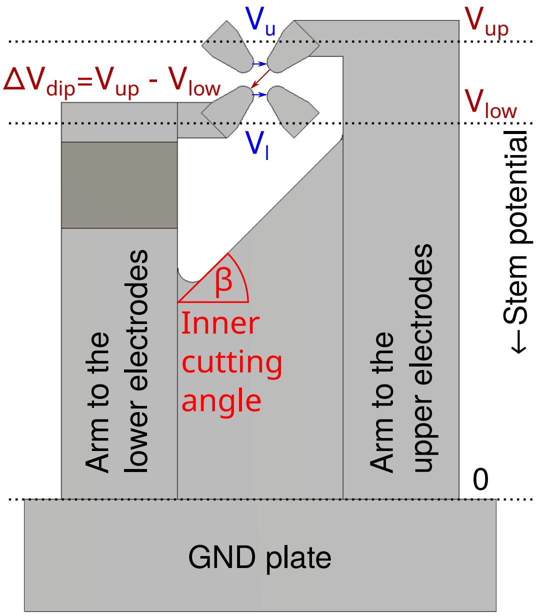

Figure 4: Front view of the model, showing the stem for one cell. V_{up} and V_{low} showing the potentials of the long and short arm in reference to the ground plate, ΔV_{dip} is the resulting dipole voltage. V_u and V_l are the calculated voltages used for the dipole factor calculation.

Results

Simulation results show a decreasing dipole factor with an increasing Δz (see Fig. 5). Depending on α the dipole factor decreases with different gradients. Simulations were performed with hexahedral and tetrahedral meshes, both mesh types show good agreement. For tetrahedral meshes the current path balance point was found around $\Delta z = 29$ mm for $\alpha = 0^\circ$ and $\Delta z = 35$ mm for $\alpha = 15^\circ$. The model with $\alpha = 30^\circ$ did not reach $DF = 1$ even at the maximum $\Delta z = 40$ mm—it stays undercompensated. Noticeable is the slight increase of the dipole factor at 10 mm.

We see a decrease in shunt impedance for increasing Δz (see Fig. 6). There are only slight differences of the shunt impedance depending on α. Interestingly hexahedral and tetrahedral meshes show quite different values of 100 kΩ m and 70 kΩ m, respectively, at $\Delta z = 0$ mm. The same phenomenon holds true for the Q-factor values (see Fig. 8).

Like expected, the resonant frequency f_0 decreases with greater Δz values. The effect is stronger for lower α (see Fig. 7).

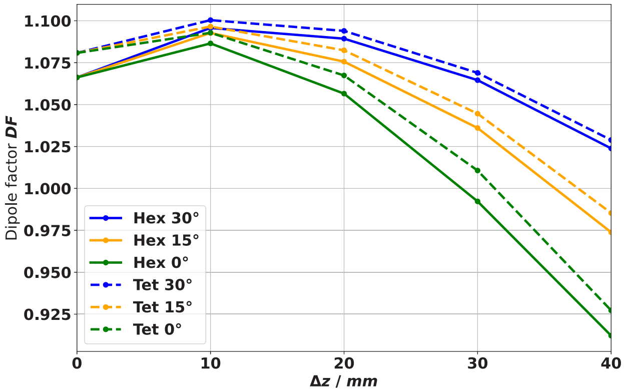

Figure 5: Dipole factor DF vs. Δz for tetrahedral and hexahedral meshes at different α.

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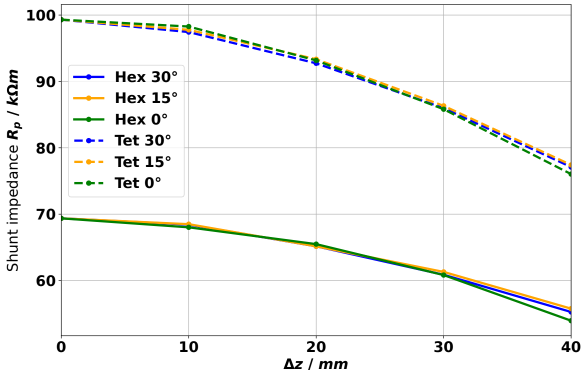

Figure 6: Shunt impedance vs. Δz for tetrahedral and hexahedral meshes at different α.

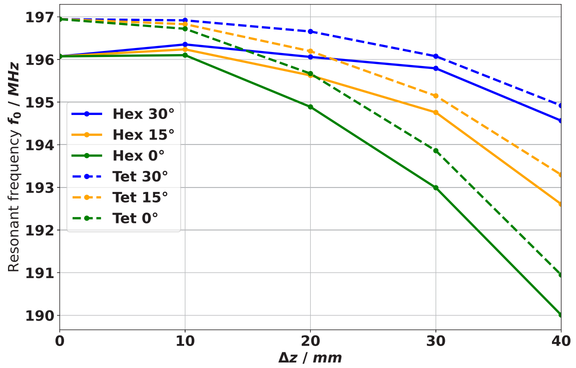

Figure 7: Resonant frequency f_0 vs. Δz for tetrahedral and hexahedral meshes at different α.

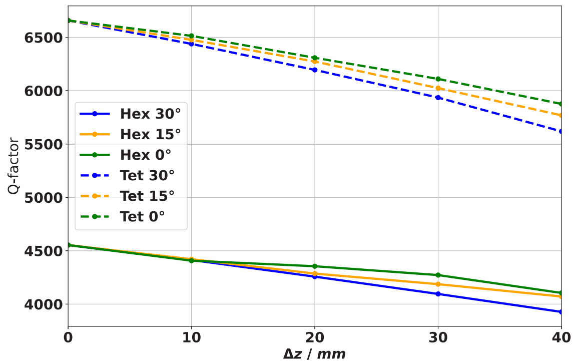

Figure 8: Q-factor vs. Δz for tetrahedral and hexahedral meshes at different α.

Discussion

We see a strong dependence of the dipole factor from α. This can be explained by the current path length. A smaller α means longer current paths and therefore compensates the dipole factor with smaller Δz values. The slight increase of the dipole factor at 10 mm can be explained by having a look at the stem thickness of 20 mm. If the stem thickness is greater than Δz, then there is no real increase of the effective current path length. So, a mitigation of dipole effect cannot be expected.

Resonant frequency changes in dependence of α can be explained by the parasitic capacitance between one stem and the next (see Fig. 3). Resonant frequency of a 4-rod RFQ can be modeled as coupled LC circuits, that means that increasing the capacitance—i.e. by increasing the parasitic capacitance—should lead to a reduction of the resonant frequency [5]. In theory a larger α should mitigate this effect, since the effective capacitive coupling area between one stem and its neighbor is reduced (see Fig. 3). The parasitic capacitance also decreases shunt impedances and Q-factors with greater Δz values. Another possible explanation is, that parts of the stem structure run in parallel with the electrodes, therefore induced currents produce more power dissipation within the structure, also dependent on Δz.

Differences in hexahedral and tetrahedral meshes are quite strong for shunt impedance and Q-factor calculations. In tendency, tetrahedral meshes produce higher accuracy results with less cells. Exact reasons for the deviation have to be reviewed.

CONCLUSION

A new type of 4-rod RFQ stem design was developed and simulated. The simulation results show that the new method can compensate the dipole field components successfully.

This is a preliminary study to prove the principle of the method. More detailed studies will be performed in the future, especially focusing on the open questions:

- To improve shunt impedances and Q-factors, which suffered from the new style dipole compensation.
- To understand the difference of the simulation results using hexahedral and tetrahedral meshes.

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