DIPOLE STABILIZING RODS SYSTEM FOR A FOUR-VANE RFQ: MODELING AND MEASUREMENT ON THE TRASCO RFQ ALUMINUM MODEL AT LNL

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Abstract
The Dipole Stabilizing Rods (DSR's) are devices used in order to reduce a priori the effect of perturbation on the operating mode of a four-vane RFQ caused by neighbouring dipole modes by increasing the frequency spacing between the TE$_{210}$ mode and dipole modes, without, in principle, affecting the quadrupole TE$_{210}$ mode. They have proven to be particularly useful in the case of coupled RFQ's whose overall length is significantly greater than the operating wavelength. In this article we present a circuit model of such DSR's, that, used in combination with a transmission line model of a four vane RFQ, has allowed us to predict the dimensioning of the DSR's in the case of the aluminium model of TRASCO RFQ. The DSR parameters and, in general, the accuracy of the model have been also confirmed by HFSS simulations and by RF measurements on the above-mentioned model.

INTRODUCTION
The effect of a perturbation (e.g. due to mechanical errors and/or misalignments) on the nominal geometry in a four-vane RFQ provokes a mixing of the operating TE$_{210}$ mode with neighbouring quadrupole TE$_{21n}$ and TE$_{11n}$ dipole modes. If the overall length L of the RFQ is significantly greater than the wavelength, the neighbouring modes can be very close to the operational one, thus enhancing the effect of perturbations. This is an issue for high intensity machine, as the case of TRASCO-SPES RFQ in construction at LNL [1], where high field uniformity is required in order to minimize beam losses. TRASCO-SPES RFQ operates at 352.2 MHz and is L=7.13 m = 8.4 $\lambda$ long. The segmentation of the RFQ[2] adopted in TRASCO-SPES RFQ by means of coupling cells (two in this case, located at L/3 and 2L/3 positions) can reduce the effect of TE$_{21n}$ perturbative terms. Therefore, a chain of N coupled RFQ's can be represented for the TE$_{21}$ (quadrupole) and TE$_{11}$ (dipole) modes by a system of N coupled transmission lines terminated by resonant loads, called end-cells tuned at the quadrupole frequency (Fig. 1)[3,4].

Moreover, the insertion of end cells raises the f$_{110}$ frequency, shifting it closer to the operational one [4]. Therefore dedicated stabilizing systems for dipole modes are needed. The usage of DSR's to be inserted in correspondence of the end-cells and coupling cells is a solution typically used for high power RFQ's [5,6,7].

THE PRINCIPLE OF DIPOLE STABILIZATION
Dipole Stabilizing Rods are conductive bars departing from the end and coupling plates and protruding into each RFQ quadrant. If they are located at a height $h_b$ on the axis of a RFQ transverse section in which electric and magnetic energy densities balance at the f$_{210}$ frequency, they almost do not affect the TE$_{210}$ mode. Moreover they couple their coaxial modes (“bar mode”) with the dipole modes (Fig. 2), thus shifting the dipole band. In fact in the quadrants 1 and 3 an electric field from the bar to the electrodes appear and a magnetic field wraps around the bars.

Figure 2: The coaxial bar mode coupling effect on the dipole mode: E field (left) and H field (right).

Therefore one can think of modelling the bar as a parallel inductance $L_b$ and parallel capacitance $C_b$ depending on bar length $l_{bar}$ added in the end and coupling cell sides the equivalent transmission line for TE$_{11}$ modes (Figure 3).

Figure 3: The equivalent circuit for TE11n modes of the RFQ in correspondence of the undercuts when bar are inserted

Now, if $l_{bar}$ is such that the equivalent admittance $Y_{eq}(\omega,l_{bar}) = j\omega(C_b + C_h) + 1/(j\omega(L_e + L_h))$ vanishes at...
the 2D dipole frequency, not only the TE_{110} frequency becomes equal to the 2D value, but the dipole free region width around the quadrupole mode is maximized. Therefore the optimization of DSR’s could be accomplished by simply tuning the TE_{110} frequency to its original 2D value. Due to the TEM nature of the bar mode inside the quadrants, an unambiguous voltage $V_b$ between the bar and the electrode can be calculated. Moreover, the capacitance per unit length can be evaluated in this part, where almost all the electric energy is concentrated, according to the relationship

$$C_b = \frac{4w_{eb}}{V_b^2}(l_{bar} - l_{end-cell}) = c_b(l_{bar} - l_{end-cell})$$

$w_{eb}$ being the electric energy per unit length.

On the other hand, the knowledge of the frequency of the bar mode allows to evaluate the inductance $L_b$. It is worth noticing that due to the field configuration in the End Cells, there is an excess of inductance with respect to the uniform coaxial line, and then an optimal bar length less than $\lambda/4$ is to be expected.

**RESULTS OF SIMULATIONS ON THE ALUMINUM MODEL**

The dimensioning and design of DSR’s has been also verified with HFSS simulations on the aluminum model of the RFQ, installed at LNL. Its overall length is $L = 3.044$ and it consists of three coupled segments. For such RFQ, calculations have given the following values for the main parameters of interest.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{110}$ (2D) [MHz]</td>
<td>339.289</td>
</tr>
<tr>
<td>$f_{210}$ (2D) [MHz]</td>
<td>350.613</td>
</tr>
<tr>
<td>$C$ [pF/m]</td>
<td>28</td>
</tr>
<tr>
<td>$C_e$ [pF]</td>
<td>0.86</td>
</tr>
<tr>
<td>$c_b$ [pF/cm]</td>
<td>0.42</td>
</tr>
<tr>
<td>$h_b$ [mm]</td>
<td>55</td>
</tr>
</tbody>
</table>

The diameter of the bar has been set to 14 mm (a realistic value for room of a cooling system) and the bar length has been varied in order to find the maximum dipole free region (fig 4). In the following figure the behavior of the dipole bands as a function of the bar length $l_{bar}$ is shown.

From this figure it is possible to notice that the length $l_{bar} = 14$ cm both creates a symmetrical dipole free region of about $\pm 6$ MHz, the $f_{110}$ frequency is equal to its 2D value within 0.1%. The results have obtained both with HFSS simulations [8] and with the transmission line model (Figure 5) and the agreement is within 1%.

**EXPERIMENTAL RESULTS**

The experimental apparatus consists of the aluminum model of the RFQ, the Vector Network Analyzer (VNA) and the setup for the bead pulling measurements [9,10].

The stabilizing rods are fixed to the end and coupling plates by means of proper screws. The VNA is the 8753ES model of the Agilent Corporation.

The first measurement has been performed without inserting the bars, and the quadrupole and dipole mode spectra measurements have given the dispersion curve of Fig. 5. In particular the quadrupole frequency $f_{210}$ is equal to 350.375 MHz (with tuners flush).

Upon insertion of the bars the new dispersion curve obtained for quadrupole and dipole modes is the following (Fig. 6), in which it can be noticed that, as predicted by theoretical analysis and simulations, the dipole frequency arrange symmetrically around the $f_{210}$, that has remained unchanged within 0.03%, by giving a dipole free region of about $\pm 6$ MHz (with tuners flush).
It has to be pointed out that such measurements exhibit a very good match with the theoretical prediction given by the Transmission Line Model and HFSS simulations (below 0.1%). The only discrepancies can be found in the behavior of the TE$_{11}$ modes predicted by the equivalent line model prior to bar insertion (in this case HFSS and measured results are some per cent higher).

The bead pulling measurements of the longitudinal evolution of the electric field for the TE$_{210}$ mode have been performed as well, with and without dipole stabilizers. In the following figures it is possible to compare the perturbing dipole contents (TE$_{11n}$ modes) on the operating mode in the two cases. It can be noticed that the insertion of the bars has decreased of about 50% the dipole perturbations, as expected.

![Figure 8: Perturbation of the dipole mode 1 on the operating mode before and after Dipole Stabilizer insertion](image)

![Figure 9: Perturbation of the dipole mode 2 on the operating mode before and after Dipole Stabilizer insertion](image)

Finally, in Fig. 10 the quadrupole component in the two cases is shown. In this case the Dipole Stabilizers have only a slight effect on the TE$_{210}$ component.

![Figure 10: Behaviour of the quadrupole component](image)

**CONCLUSIONS**

The RF measurements performed on the aluminum mode of the RFQ equipped with dipole stabilizers have shown that the combined predictions of the Transmission Line model and of HFSS simulations are accurate and can be reliably used in phase of testing of such devices on the high-power TRASCO-SPES RFQ. Therefore one could be confident that the cooled DSR’s that will be constructed and brazed on the coupling and end plates could be directly mounted on the cavity. Moreover, the Transmission Line Model has been updated and, so that the tuning algorithm of the RFQ that makes use of 96 slug tuners can be improved.

**REFERENCES**


[8] HFSS 8.5 distributed by ANSOFT CORPORATION Pittsburgh, PA 15219-1119 USA
