THE IFMIF RFQ REAL-SCALE ALUMINUM MODEL: RF MEASUREMENTS AND TUNING

A. Palmieri, F. Grespan, INFN/LNL, Legnaro (PD) Italy

P. Mereu, D. Dattola, INFN, Sez. di Torino, Torino, Italy

G. Cotto, University of Torino, Torino, Italy

Abstract

In order to validate the tuning and stabilization procedures established for the IFMIF RFQ, a campaign of low power tests on an aluminium real-scale RFQ built on purpose has been carried out. Such campaign consisted of the determination of mode spectra, the measurements of the electric field distribution with bead pulling technique, and the implementation of the tuning procedure. The main outcomes and results obtained are reported in the article.

RF LOW POWER TEST DESCRIPTION

The aluminum model of the IFMIF EVEDA RFQ is 9.9 m long with constant section (corresponding to the last cell), divided in 8 modules 1.1 m long each and two modules 0.55 m long in the central part. The main features of such RFQ are:

- Vane undercuts at the extremities of the first and last module, whose dimensions were calculated with HFSS simulations.
- 144 holes of 90 mm diameter, for the housing of tuners and the possibility of inserting a coupling cell in the middle, if needed.
- Possibility of insertion of dipole stabilizing rods foreseen both in the end and in the coupling plates, whose transverse position and length can be varied.
- A set of tuners of radius a=45 mm, whose number can be set up to 100 whose depth inside the cavity can vary from 0 mm (flush tuners) to 80 mm and whose accuracy is 0.02 mm. Such tuners are conceived to be easy to set and can also be interfaced with stepping motors, if needed. The nominal number of tuners installed is equal to 88, that is N_T=22 tuners/quadrant.
- A tunable end plate, which can vary the boundary conditions via the 0-50 mm insertion [extraction] of the movable part with respect to the flush position. In this way the end-cell frequency can be varied, thus permitting the tuning of the boundary conditions.
- Possibility of 1m sliding of each module on the support for adjustment, rods insertion etc.

Figure 1: The aluminium model of the IFMIF RFQ set up for measurements at LNL (left) and the bead pulling system (right) .

The system for bead pulling measurements was designed and constructed by INFN Torino and consists of a set of four motors in dc that are computer controlled with a LABVIEW routine, four dielectric threads, a system of pulleys, and four ogive-shaped beads of delrin (εr=3.7) of 10 mm diameter which move in each quadrant in the zone where electric energy is predominant. The tension of each thread can be varied by acting on a screw and its positions can be varied along the bisector of each quadrant. This system allow the positioning of the thread in the quadrant with a few tenth of mm precision, and the possibility of controlling in a repeatable way the longitudinal positioning of the bead. By using the Slater's perturbation theory, it is possible to relate the module of the electric field from the phase shift $\Delta\phi(z)$ induced by the beads as they move longitudinally along the quadrant. Such shift is measured with an Agilent 8753ES Vector Network Analyzer.

INITIAL RF MEASUREMENTS

RF Mesasurements with Flush Tuners

The preliminary measurements were performed with the 88 tuners and the end plate in flush position, with no rods and coupling elements inserted. The quadrupole fundamental mode was at 172.6 MHz, with Q_L=3600 and the upper quad mode was about 700 kHz above. The mode sequence is the same as predicted by HFSS simulations and transmission line models and the mode frequencies match with code within 0.5%. Moreover, the dipole modes closest to the fundamental quadrupole one are nearly symmetric with respect to it and the dipole free region around the TE_{210} mode is about ±1.6 MHz. The symmetry of this dipole-free region has driven the choice of skipping the installation of dipole stabilizing rods also in the following measurements.

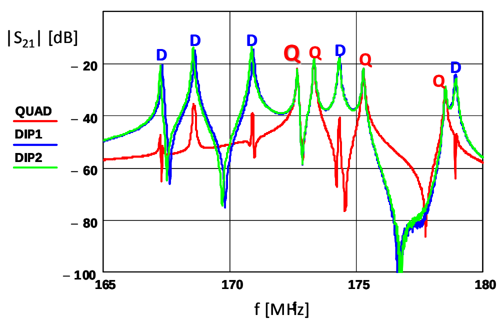

Figure 2: Mode spectra of the Aluminum RFQ.

The bead pulling measurements on the RFQ with flush tuners highlighted that the quadrupole component is less than 2%, showing a good longitudinal mechanical uniformity among the four electrodes, while the dipole component (±10%) shows that some asymmetry between the four electrodes occurred.

RF Measurements with Inserted Tuners

In order to reach the nominal frequency of 175 MHz, all the 22 tuners were set at δh_0=30 mm penetration.

The positions of the tuners z_t, t=1,..,N_T are indicated in Figure 3

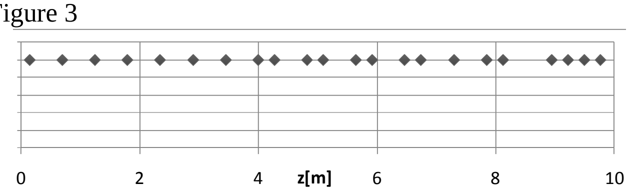

Figure 3: Tuners positions along the RFQ.

This operation had little effect on dipole component, but introduced a large quadrupole drop, due to the irregular spacing of tuners, as well as to the 30 mm penetration, somehow higher than the nominal penetration of 14.6 mm needed to shift from the theoretical cut-off frequency of 174 MHz to the operational frequency [1].

The measured frequency was equal to 174.961 MHz.

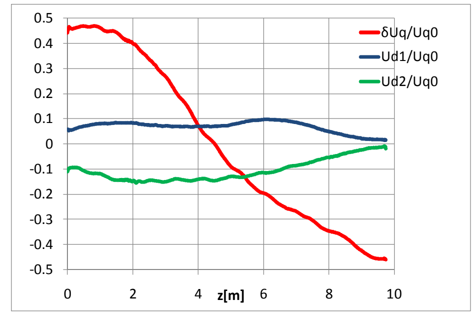

Figure 4: Perturbative components of the RFQ, with tuners inserted at 30 mm depth.

TUNING STRATEGY

The goal of the tuning strategy is to reduce the perturbative components up to a determined value, tipically driven by beam-transmission considerations, that is $|\delta U_q/U_{q0}|<m_Q$, $|\delta U_{d1}/U_{q0}|<m_{d1}$ and $|\delta U_{d2}/U_{q0}|<m_{d2}$. It is worthwhile to remember that for IFMIF-EVEDA RFQ, the proposed limits are $m_Q= m_{d1}= m_{d2}=0.02$ Since the tuning range is defined as $2\delta h_0$, in this case the tuning procedure can be validated if the goals are reached with all the tuners depth included in the interval $[0, 2\delta h_0]$ [1]. The basic idea of tuners perturbation compensation is that the capacitance (or inductance) perturbative terms [2] can be spanned in series of the quadrupole and dipole eigenfunctions φ_{qm} and φ_{dm} Therefore, a set of coefficients $\{b_{qm}\}_{m\in\mathbb{N}}$, $\{b_{d1m}\}_{m\in\mathbb{N}_0}$, $\{b_{d2m}\}_{m\in\mathbb{N}_0}$ exist such that:

$$\delta C_{QQ} = \sum_{m=1}^{NQ} b_{qm}\varphi_{qm},\ \delta C_{Qd1} = \sum_{m=0}^{Nd1} b_{d1m}\varphi_{dm},\ \delta C_{Qd2} = \sum_{m=1}^{Nd2} b_{d2m}\varphi_{dm}$$

where NQ, Nd1 and Nd2 are the number of harmonics used.

Now, provided that the measured components can be spanned in series of RFQ eigenfunctions as it follows

$$a_{qn} = \int_0^{\ell} \Delta U_q \varphi_{qn} dz\ \ n\in\mathbb{N},\ a_{d1n} = \int_0^{\ell} U_{qd1}\varphi_{dn} dz\ \ n\in\mathbb{N}_0,$$

$$a_{d2n} = \int_0^{\ell} U_{qd2}\varphi_{dn} dz\ \ n\in\mathbb{N}_0$$

The substitution of the above expression in the perturbative development of the voltages [2], leads to the following matrix equations

$$\mathbf{C}^{(q)}\mathbf{b}_q = \mathbf{a}_q,\ \mathbf{C}^{(d)}\mathbf{b}_{d1} = \mathbf{a}_{d1},\ \mathbf{C}^{(d)}\mathbf{b}_{d2} = \mathbf{a}_{d2}$$

where the matrices $\mathbf{C}^{(q)}$ and $\mathbf{C}^{(d)}$ are defined as:

$$C_{nm}^{(q)} = -\frac{\omega_0^2}{4C(\omega_0^2-\omega_{qn}^2)}\int_0^{\ell} \varphi_{q0}(z)\varphi_{qn}(z)\varphi_{qm}(z)dz\ \ n,m\in\mathbb{N}$$

$$C_{nm}^{(d)} = -\frac{\sqrt{2}\omega_0^2}{4C(\omega_0^2-\omega_{dn}^2)}\int_0^{\ell} \varphi_{q0}(z)\varphi_{dn}(z)\varphi_{dm}(z)dz\ \ n,m\in\mathbb{N}_0$$

Therefore it is possible to synthesize the perturbation by solving the above systems. Now, in order to cancel these perturbations, the inductance profile along the RFQ should satisfy the relationships

$$\begin{cases} \dfrac{\delta L_{QQ}}{L} = -\dfrac{\delta C_{QQ}}{C} \\ \dfrac{\delta L_{monopole}}{L} = 0 \\ \dfrac{\delta L_{Qd1}}{L} = -\dfrac{\delta C_{Qd1}}{C} \\ \dfrac{\delta L_{Qd2}}{L} = -\dfrac{\delta C_{Qd2}}{C} \end{cases} \Rightarrow \begin{cases} \dfrac{\delta L_1}{L} = -\dfrac{1}{4}\dfrac{\delta C_{QQ}}{C} - \dfrac{\sqrt{2}}{4(1+h)}\dfrac{\delta C_{Qd1}}{C} \\ \dfrac{\delta L_2}{L} = -\dfrac{1}{4}\dfrac{\delta C_{QQ}}{C} + \dfrac{\sqrt{2}}{4(1+h)}\dfrac{\delta C_{Qd2}}{C} \\ \dfrac{\delta L_3}{L} = -\dfrac{1}{4}\dfrac{\delta C_{QQ}}{C} + \dfrac{\sqrt{2}}{4(1+h)}\dfrac{\delta C_{Qd1}}{C} \\ \dfrac{\delta L_4}{L} = -\dfrac{1}{4}\dfrac{\delta C_{QQ}}{C} - \dfrac{\sqrt{2}}{4(1+h)}\dfrac{\delta C_{Qd2}}{C} \end{cases} \quad (1)$$

Since the tuners are located in discrete positions, these relationships are fulfilled only in correspondence of the tuners: in particular, if the functions $p_t(z) = 1/\sqrt{2a}$ if $z_t - a \le z \le z_t + a$ and 0 otherwise are introduced, it is possible to project the inductances of Equations (1) on this subset of functions (here i=1,…4 is the quadrant index), thus obtaining the required inductance variations

$$\delta L_{ti}'(z) = \int_0^{\ell} \delta L_i(z) p_t(z) dz \, p_t(z)$$

Finally, recalling that each inductance variation is linked to the corresponding tuner depth variation by the relationship $\delta L_i'(z) = 2\chi \delta h_i(z)$, it is possible to calculate the needed depth variation. The parameter χ can be evaluated with appropriate simulations (with SUPERFISH or HFSS) and/or the help of the Slater formula. The matrix $\underline{\underline{\mathbf{\delta h}}}$ can be transformed into the modal function basis, thus obtaining the three vectors of N_T elements $\mathbf{\delta h_Q}$, $\mathbf{\delta h_{d1}}$, $\mathbf{\delta h_{d2}}$ such a way that it is possible to decouple the contributions to the quadrupole and dipole modes in the tuning algorithm. Such vectors can be multiplied by appropriate gain parameters g_Q, g_{d1} and g_{d2}, in order to speed up the tuning convergence process up to the required values, thus obtaining the actual depths to be set in the RFQ.

TUNING RESULTS

The tuning procedure results are outlined in the following diagrams: four tuning iterations were needed in order to reach the voltage uniformity targets and the frequency of 174.997 MHz: the first three tuning iteration were performed by using a relatively high gain values (from 3 to 5) and low number of harmonics (NQ=Nd1=Nd2=4), while, in the last iteration the gains were set to 1 and 10 harmonics were used.

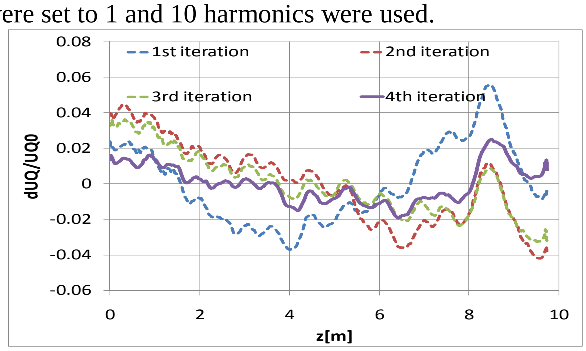

Figure 5: Evolution of the Q component.

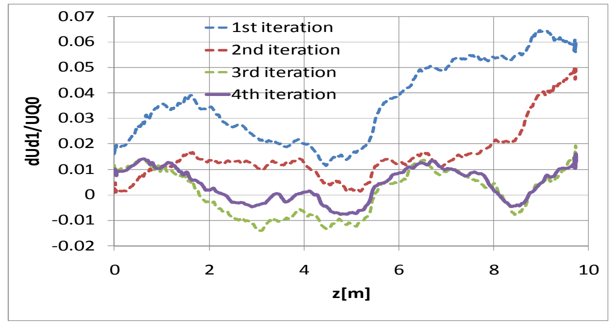

Figure 6: Evolution of the D1 component.

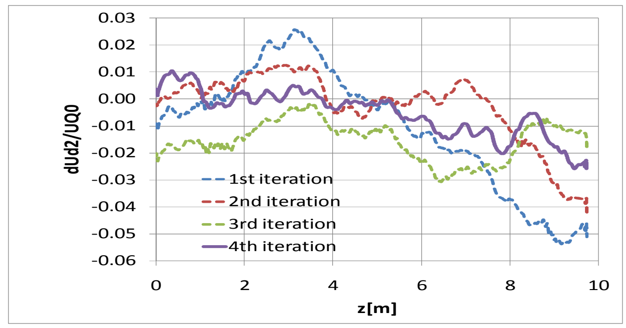

Figure 7: Evolution of the D2 component.

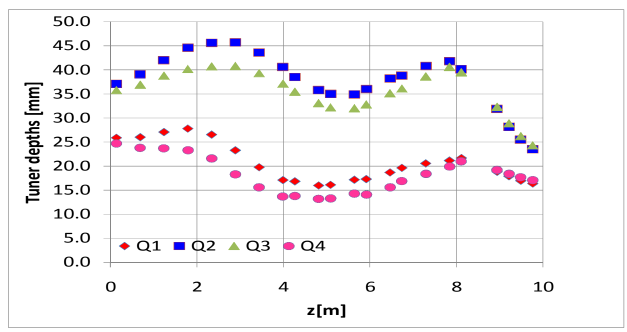

Figure 8: Final tuner settings.

CONCLUSIONS

The measurements performed on the aluminium model have shown that the tuning algorithm allows, upon careful choice of the gains and of the harmonics, a convergence in a few number of iteration. Moreover, only a part of the tuning range was exploited to reach such goal. Therefore the prompposed method appear promising in view of its usage on the definitive copper RFQ

REFERENCES

[1] F. Grespan et al. LINAC 2008 Victoria (Canada)
[2] A. Palmieri andF. Grespan, these proceedings