FIELD TUNING OF THE TRASCO RFQ

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Abstract

In the frame of the TRASCO/ADS project, the Italian study for an accelerator driven system for nuclear waste transmutation, we have built and developed a 3 m aluminium RFQ cold model divided in three resonantly coupled segments.

This paper presents the results of the RFQ tuning. The tuning procedure was performed by employing the bead-pulling technique, aimed to obtain a constant transverse electric field along the RFQ with a field error of the order $|\Delta V/V| \leq 2\%$. The procedure and the tuning algorithm based on the analysis of the second derivative of the measured data will be described in details.

1 INTRODUCTION

A CW RFQ (Radio Frequency Quadrupole) is under construction at LNL. It is intended as the injector of a high intensity proton linac to be used in ADS (Accelerator Driven System) for the TRASCO project [1]. The construction of the first part of this proton linac at LNL, up to the energy of 100 MeV, has been envisaged as the primary linac of an ISOL facility.

One of the major constrains concerns the achievement of a transverse electric field having a field $|\Delta V/V| \leq 2\%$ along the RFQ; this will allow a particle transmission higher than 95 % [2]. We have built aluminium RFQ cold [3] model having three resonantly coupled segments to carry out bead-pulling measurement and check tuning procedure.

2 DATA ANALYSIS AND ALGORITHM

The algorithm is based on the direct integration of the wave equation, for small deviation from the desired field distribution. Respect to the method based on the expansion of the measured field in normal modes and consequent application of the eigen-problem perturbative theory [4], this method has the advantage that can be applied even when eigen-vectors are non-orthonormal. This is the case of resonantly coupled RFQs, where the normal modes can be calculated either by the transmission line model or by direct simulations, but it is not easy to define a scalar product respect to which the modes are normal. Moreover, the use of the direct equation can give any field shape, not necessarily the flat quadrupole field [5].

In order to explain the method, let us consider the case of one single mode (TE_{21}); the field configuration is determined by $B_z(x,y,z,t)$, obeying to the equation:

$$c^2\nabla^2 B_z(x,y,z,t) - \frac{\partial^2 B_z(x,y,z,t)}{\partial t^2} = 0 \qquad (1)$$

With the ansatz $B_z(x,y,z,t) = F\ (x,y)V(z)e^{j\omega t}$ the transverse dependence is determined by solving the eigenvalue equation:

$$c^2\nabla^2 F + \omega_c^2(z)F = 0 \qquad (2)$$

for the given mode configuration and geometrical boundary conditions; $\omega_c(z)$ is the mode cut-off frequency and, if the geometry varies longitudinally, it is a function of z. Substituting the previous ansatz in Eq. (1) we get:

$$c^2\frac{\partial^2 V}{\partial z^2} - (\omega_c^2(z) - \omega^2)V = 0 \qquad (3)$$

and for small deviations from the measured quadrupole frequency ω_0 with associated wavelength λ_0:

$$\left(\frac{\lambda_0}{2\pi}\right)^2 \frac{\partial^2 V}{\partial z^2} - 2\frac{\omega_c(z)-\omega_0}{\omega_0}V = 0 \qquad (4)$$

Given the field measurement $V(z)$, the unknown in Eq. 4 is $\omega_c(z)$. In particular when one is looking for a flat field, the desired condition is $\omega_c(z)=\omega_0$ and the $\omega_c(z)$ solution of Eq. 4 with the measured field is due to the mechanical errors. Ideally one would move the tuner penetrations P_i so as to cancel the errors, i.e.:

$$P_i = -\frac{\omega_c(z_i)}{\chi} \qquad (5)$$

$$(i = 1..N,\ N = \text{number of the tuners})$$

where $\chi = \frac{\partial \omega_c(z)}{\partial P}$ is the tuner sensitivity, in first approximation supposed to be independent from the tuner position, and z_i the tuner location. This procedure can be iterated.

In practice one has a finite number of tuners, and a measured field rather noisy, so the difficulties lie in calculating the second derivative of the measured field properly smoothed, taking into account all the available tuners. One has to keep in mind that a perturbation with wavelength smaller than the distance between two neighbour tuners cannot be corrected.

This method has been extended [6] to include the perturbation given by the neighbour's dipole band. This is accomplished by an extension of the Eq. 4 over the four RFQ quadrants:

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$$\left[2\frac{\omega_0-\omega^j(z)}{\omega_0}+\left(\frac{\lambda_0}{2\pi}\right)^2\frac{\partial^2}{\partial z^2}\right]V^j(z)+\frac{\omega_0-\omega_d}{\omega_0}\times \tag{6}$$
$$\left[\left(V^j(z)+V^{j+1}(z)\right)+\left(V^j(z)+V^{j-1}(z)\right)\right]=0$$

($j\pm1\equiv j\pm1$ mod 4)
where:

- $V^j(z)$ is the measured field in the j^th^ quadrant,
- ω_d is the calculated dipole cut-off frequency, that determines the coupling between TE_{21} and TE_{11} bands,
- $\omega^j(z)$ is the quadrant local frequency, determined by geometrical details, i.e. machining errors and tuner penetrations (at the various locations one has generally one tuner per quadrant).

In perfect analogy with the procedure shown before, to get a flat field, one solves Eq. 6 for the measured field and then corrects the $\omega^j(z)$ dependence with the tuners. It should be mentioned that the tuner positions at this point are not fully determined, and the remaining degrees of freedom are used to maintain the frequency and to cope with the field matching at the coupling cells. The tuning procedure has been implemented in the program TRITA (TRASCO RFQ Iterative Tuning Algorithm).

3 RFQ UNDER TEST AND TUNING PROCEDURE

3.1 Experimental Apparatus

The experimental apparatus (bead-pulling system Fig. 1) consists of four empty cylindrical PVC dielectric beads 20 mm long with a diameter of 24 mm, four cc motors driving the beads by means of a nylon thread of 0.23 mm diameter and, a Vector Network Analyzer (VNA) HP 8753ES. Each bead touches a couple of adjacent electrodes, so the best reproducibility can be achieved.

Due relatively large diameter of the beads, the wires are in a low electric field region. This avoids perturbations in case of wire asymmetry. The wires cause only a slight change of quadrupole frequency, $\Delta\omega_q \approx -8\,\text{kHz}$.

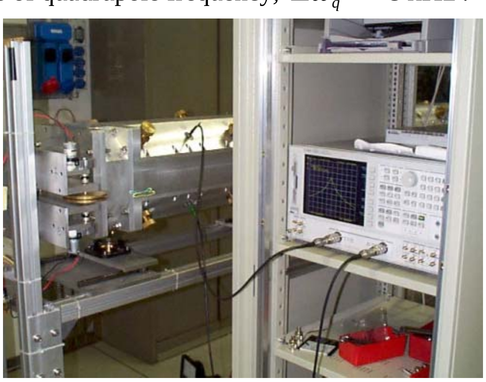

Figure 1: Experimental set-up for the bead-pulling measurements

We perform phase shift measurements [3] that provide a relative measurement of the electric field. This measurement method is practically unaffected by temperature variation since a single phase plot is taken in about 40 sec and that the E-field variation along the structure is shown during the measurement, on the VNA screen. The flatness $FL=\left|\Delta V/V\right|$ is easily evaluated.

Phase measurement is performed with a VNA resolution bandwidth RBW=100 Hz, resulting in a phase error of 0.05 deg. Since VNA phase dynamic accuracy is about 0.15 deg., the total measurement error is 0.2 deg. corresponding to a flatness error of 0.21 %.

3.2 Aluminium RFQ and tuning procedure

RFQ transverse section is shown in Fig.2 while main parameters are listed in Tab.1.

Table 1: RFQ main parameters

Quad. Freq. with tuners flush	350.60 MHz
Dip Freq.	339.08 MHz
Quad Freq with tuner inserted	352.20 MHz
Average Tuner insertion	13 mm

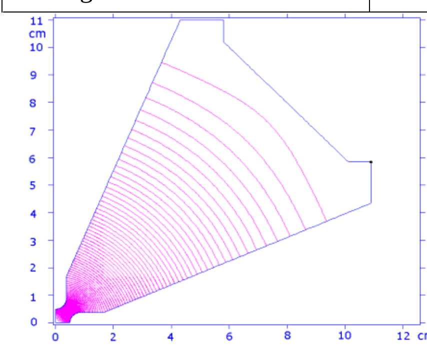

Figure 2: RFQ transverse section, one quadrant (SuperFish Simulation)

In Fig. 3 the quadrupole and dipole dispersion curves are shown.

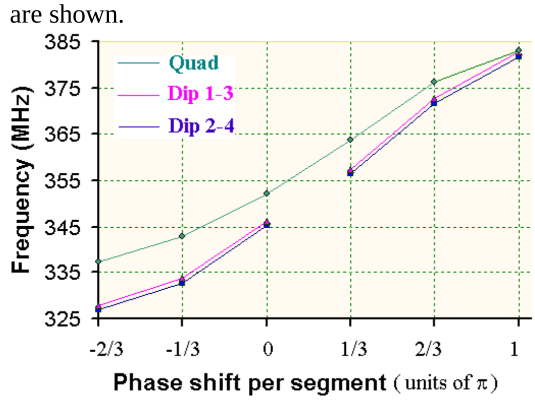

Figure 3: quadrupole and dipole measured dispersion curve at the end of the tuning procedure.

Notice that the dipole and the quadrupole bands are not separated. The two dipole bands are almost overlapping. It is a sign of small mechanical errors.

The tuning procedure we have established is the following:

1) Tune both end cells (we did it by varying the undercut region and the end cell plate) making measurement on one single RFQ segment. Tuners should be maintained in the middle of the tuners range;

2) Tune the coupling cells by joining together 2 RFQ segments (as we did for the end cells);

3) Join all the segments. Apply the code all the time needed to get flat field configuration at the level $|\Delta V/V| \le 1\%$ for each individual quadrant segment by segment (see Fig. 5). This is very important since, at the end of tuning procedure, this will be the lowest achievable field flatness.

Tuners are set at an insertion value of 15 mm (Fig. 4), i.e., 2 mm more then the foreseen value since both coupling and end cells were not exactly tuned.

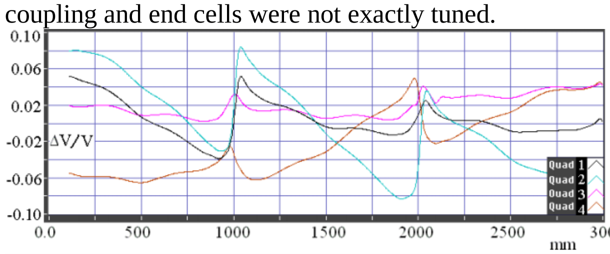

Figure 4: Normalized electric field for the 1st. bead-pulling measurement.

In Fig. 5 the 5th measurement is shown. As already mentioned, two steps exist, while field error for each quadrant related to a single segment is almost $FL \approx [1 \pm 0.21]\%$

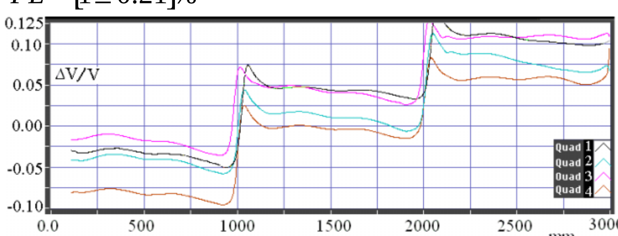

Figure 5: Normalized electric field for the 5th. bead-pulling measurement step

4) Make the average field level in the three segments equal for all the quadrants. The tuner insertions for the tuners beside the coupling cells are calculated by the relation:

$$\Delta P_l^{\,j} = -\frac{2\omega_0 (V_l^{\,j} - V_r^{\,j})}{G(V_l^{\,j} + V_r^{\,j})};\ \Delta P_r^{\,j} = \frac{2\omega_0 (V_l^{\,j} - V_r^{\,j})}{G(V_l^{\,j} + V_r^{\,j})}$$

where $V^j_{l,r}$ are the field magnitudes for the quadrant j at the left and at the right of the coupling cell, ω_0 is the measured quad frequency, and G is a constant related to the tuner sensitivity χ.

The resulting field flatness is in Fig. 6. We have got an overall field variation $FL \approx [2 \pm 0.21]\%$.

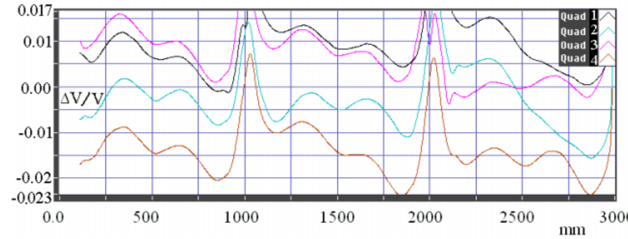

Figure 6: Normalized electric field for the 6th measurement step

5) In case of a final frequency different from the target value, the frequency can be shifted whithout spoiling the field flatness simply moving all the tuners keeping the quadrupole symmetry.

The relative quadrupole field component is shown in Fig. 7. For the case of the 1st meas., a strong perturbation due to the neighbour modes is evident.

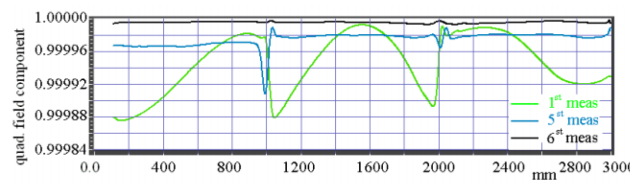

Figure 7: Energy normalized quadrupole field component

We have tuned the cold model RFQ at the target frequency value. It makes us confident that the algorithm can be applied for the tuning of the *7.13 m* long TRASCO copper RFQ where 104 tuners are available.

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