# TUNING PROCEDURE OF THE 5 MEV IPHI RFQ

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*Abstract*

The 5-MeV High Intensity Proton Injector (IPHI) RFQ is constituted by the assembly of four 2-m long segments. Its non-homogeneity and the severe electromagnetic tolerances have required the development of a comprehensive tuning formalism. This formalism interprets field measured in real RFQ in terms of ends detuning and slug tuners commands. End regions detuning is corrected by plate thickness and dipole rods lengths adjustments. Final slug tuners depths are determined at the last tuning step. The different tuning procedures are presented in this paper.

## 1 INTRODUCTION

For the IPHI RFQ tuning, we have developed a complete formalism [1] that is able to satisfy very severe requirements (typical of high intensity injector), while taking into account its electromagnetic specificities (non-constant accelerating voltage $V_p(z)$, transverse resonance frequency varying longitudinally $f_c(z)$ ), and ensuring fast convergence. This paper presents the different devices tuning procedures that have been validated on our RFQ cold-model.

## 2 RFQ SPECTRAL ESTIMATION

With the help of the spectral theory [1], the discrepancy between the real cavity and the ideal one is expressed through quadrupole (*cQi*) and dipole (*cSj & cTk*) modal components. In a ideally tuned RFQ :

- all components are null except one *cQi* that corresponds to the accelerating mode. When this cQ is equal to 1, the resonance frequency is tuned. The other *cQi* correspond to the spectral expansion of the accelerating voltage distribution on the higher-order eigen- base vectors of the ideal RFQ. They are close to zero when the voltage profile is close the nominal value;
- $cSj = cTk = 0$ when the dipole disequilibria are corrected.

## 2 SLUG TUNERS COMMANDS

On the whole, the positions of 128 slug tuners distributed along this 8-m long RFQ have to be adjusted. Our formalism [1] makes possible the computation of the slug tuners displacements [2] that command individually each modal component of the accelerating voltage. The operator selects the *cQi, cSj & cTk* to be tuned simultaneously, and the code computes the correspondent linear combination of displacements.

One tuning iteration consists in a bead-pull measurement of the voltages *Ui(z)* in the 4 quadrants [3], the data analysis by the code developed from our formalism, and the displacement of the tuners. Series of tuning tests of our RFQ cold-model [2] have demonstrated that within less than 4 iterations we achieve a simultaneous convergence of all the parameters with :

- a quadrupole component $U_Q(z)$ of the accelerating voltage tuned better than ±1 % w/r to the nominal profile $V_p(z)$ all along the cavity;
- dipole components lower than ±1 % x $U_Q(z)$;
- moreover, even in the case of highly irregularly spaced tuners, the normalized quadrant voltages errors, that accumulate the quadrupole and dipole errors, can be smaller than $7.10^{-3}$.

As a validation of the ability to tune the IPHI RFQ,

- a variable voltage profile has been tuned in a 2-m long segmented RFQ cold-model moving 48 plungers within 4 iterations, each one lasting about 20 minutes;
- the convergence of the tuning has been validated in the cold-model configured as the non-homogeneous real profile first segment with irregularly spaced tuners.

## 3 DIPOLE RODS TUNING

### 3.1 Model vs. real RFQ discrepancy

The first tests of the tuning of a 2-m long RFQ cold-model with the slug tuners have diverged : the dipole components were systematically increasing as soon as their commands were considered within the slug tuners displacements computation. For these tests no dipole rods were mounted on the ending plates.

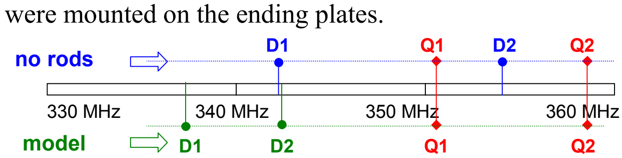


Fig. 1 : Frequencies of the first modes (measured vs. model)

In this situation, we observed up to the fourth order the alternation of a dipole mode followed by a quadrupole mode (Fig. 1), whereas the model anticipates that the first 2 modes are dipolar, and that the 2 following ones are quadrupolar.

The tuners commands computation is based on the first order perturbation theory of spectral operators; each i-th modal command is proportional to the corresponding i-th component of the accelerating voltage, and also to $f_q - f_i$, $f_q$ and $f_i$ being respectively the quadrupole and the i-th modes frequencies. In our test, $f_{Q1} - f_{D2} <0$, though the model predicts that $f_{Q1} - f_{D2} >0$ so the correction of the commands of the dipolar components is wrongly signed, and consequently the tuning diverges.

An other measurement illustrates the discrepancy between the model and the real RFQ. The voltage profiles of the first dipole mode (measured with the bead-pull test bench) show steep slopes at both ends (Fig.2). The strong detuning of these ending regions implies that the eigen vectors of the dipole modes used in the commands computation are too far away from the real vectors. This inadequacy contributes to the divergence of the tuning.

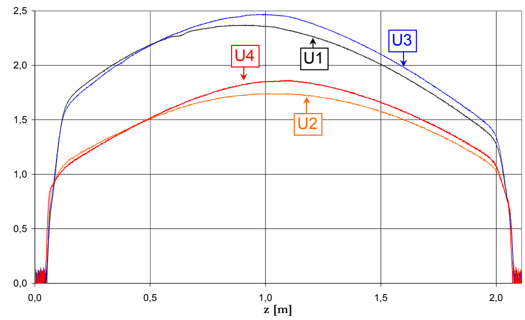


Fig. 2 : Voltage profiles of the 1rst dipole mode (no rods)

The voltages slopes can be related to equivalent ending loads for this dipole mode : here, the susceptances of these loads are negative.

## 3.2 Adjustment of the 'dipole' rods

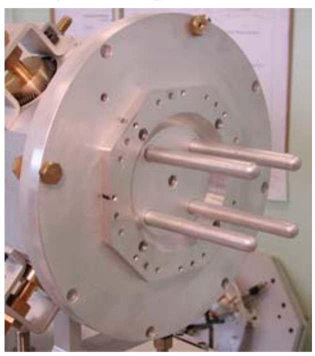

Fig. 3 : ending plate of the cold-model with dipole rods

The rods (Fig. 3) have been inserted with their nominal length [4] :

- the quadrupole mode frequencies $f_{Q1}$ and $f_{Q2}$ have been only slightly modified (Table 1). It experimentally confirms the position chosen accordingly to 3D simulations [4] with the criteria that rods do not perturb the quadrupole modes;
- the modes are ordered in agreement with the model.

In order to bring $f_{D1}$ and $f_{D2}$ closer to the nominal values, the rods lengths have been decreased by 20 mm. A very good correspondence has then been reached between the measured frequencies of the first modes and their ideal values.

Table 1: Frequencies of the quadrupole ('Q') & dipole modes ('D') expressed in MHz

| | $f_{D1}$ | $f_{Q1}$ | $f_{D2}$ | $f_{Q2}$ |
|---|---|---|---|---|
| Measured (No rods) | 342,25 | 350,506 | 354,091 | 358,495 |
| Model (Ideal RFQ) | 339,1 | 350,8 | 347,2 | 358,6 |
| Measured (Rods - nominal lengths) | 337,3 | 350,6 | 342,4 | 358,55 |
| Measured (Rods - adjusted lengths) | 339,7 | 350,6 | 347,5 | 358,6 |

This better situation can also be seen with the dipole mode voltages profiles. The presence of the adjusted rods has decreased the inductive component of the end loads and has led to a clear straightening of the voltages slopes (Fig. 4).

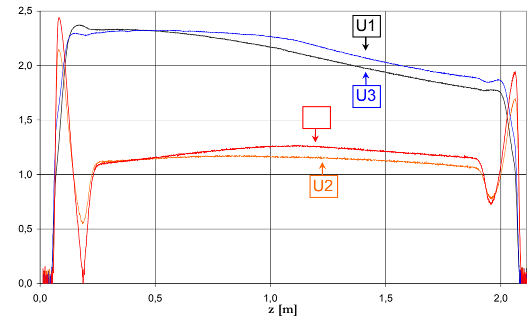


Fig. 4 : Voltage profiles of the 1st dipole mode (adjusted rods)

## 3.3 Convergence criteria

After having adjusted the rods lengths, the tuning of the 2-m long RFQ has perfectly converged within 3 steps. The tuning algorithm supposes small perturbation of the ideal RFQ. The rods play the role of bringing the dipole modes frequencies and voltages close enough to the nominal values and prevent a too big discrepancy that leads to divergence. A criteria can be introduced in order to estimate this discrepancy:

- in non-segmented RFQs, the n-th longitudinal mode frequency $f_n$ can be related to the frequency of the first mode as : $f_n^2 = f_1^2 + (n-1)^2\, df(n)^2$. We introduce *df(n)* as the 'quadratic shift frequency', that is equal to *c/2L* in a homogeneous RFQ (L=length);
- in a segmented RFQ, a similar relation can be used where : $df(n) = \sqrt{\left|f_n^2 - f_{nSegm}^2\right|} \Big/ \left(n - n_{Segm}\right)$, and $f_{nSegm}$ stands for the accelerating mode frequency.

The dipole modes are considered to be correctly tuned when the measured *df(n)* agrees with the nominal one, meaning that the RFQ length 'seen' by the correspondent mode is equal to the mechanical length.

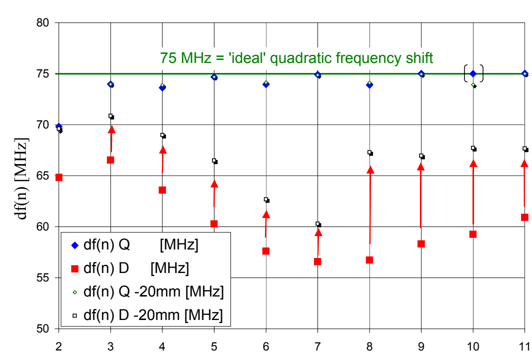


Fig. 5 : Adjustment of the 'quadratic shift frequency' of the quadrupole (Q) and dipole (D) modes

This criteria has been used when tuning the cold-model, exactly configured as the first segment of the IPHI RFQ. Before moving the tuners, the length of the rods has been shortened by 20 mm in order to get the dipole df(n) closer to the 75 MHz corresponding to the effective mechanical length of the RFQ. In that state, the resonance frequencies of the lower orders were in good agreement with the theoretical values (Fig. 5).

## 4 END PLATES TUNING

The tuning of the ending regions with respect to the quadrupole mode is made by machining the thickness of the ending plates. The end region mismatch is characterized by a parameter $\Omega = L x \Delta f$, expressed in m.MHz, where $L$ is the RFQ half-length and $\Delta f$ is the difference between the mismatched resonance frequency and the nominal cut-off frequency ([5]).

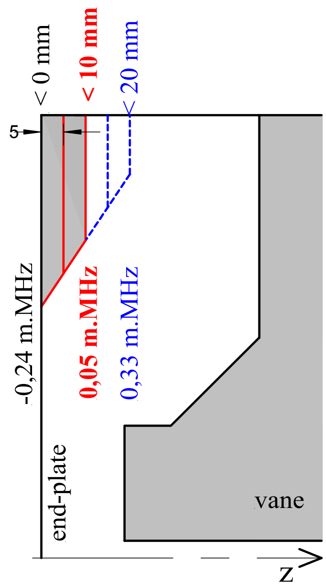


Fig. 6 : End-plate

In our RFQ cold-model end region, by design, with the help of 3D electromagnetic Soprano simulations, the nominal thickness is defined at a mid-position:

1- at the nominal end-plate thickness (=10 mm), Ω is very close to zero,

2- layers can be removed or added in order to cover a [-0,24 m.MHz , + 0,33 m.MHz] adjustment range (Fig. 6).

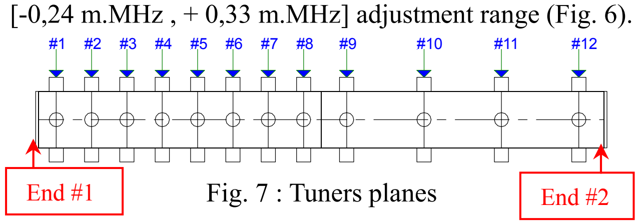


Fig. 7 : Tuners planes

The extraction of Ω requires at least 3 measurements with different voltage excitations [1], that are easily achieved by moving tuners at some distance of the end being tuned. In this test, the RFQ has two segments, 1 meter long each. Five excitations are used: (i) all tuners flush, (ii) S-like: tuners are moved inwards in quadrant #1 and outwards in quadrant #3, and in the same way, (iii) T-like, (iv) X-like and (v) Y-like. Slugs are moved in planes #6, 7 and 8 of segment #1 (Fig. 7). Ω may be computed using all 5 excitations together, in a least-square sense, or using all possible triplets. The latter are used to estimate the standard deviation of the extraction process:

| end #1 plate (mm) | average (m.MHz) | std. dev. (m.MHz) |
|---|---|---|
| 0 | –0.120 | 0.032 |
| 10 | +0.001 | 0.055 |
| 20 | +0.300 | 0.086 |

The tuning sensitivity is easily derived from the measurement, and seems to be somewhat smaller than expected. The nominal plate thickness is well-adjusted, up to the present measurement accuracy.

## 5 CONCLUSION

We have developed a complete formalism that permits :

- the computation of the slug tuners positions from bead-pull measurement of the voltage profiles. In a small number of iterations (≈5), all the electromagnetic parameters converge simultaneously. This convergence has been tested on our cold-model in the complete configuration of the IPHI RFQ (segmented, non-homogeneous, tuners irregular distribution);
- the estimation of the end region mismatch from a set of different voltage excitations. Experimental tests have shown a good agreement between this method and the results expected from the 3D simulations.

For the dipole rods adjustment, a practical criteria has been introduced, that ensures the convergence of tuning by preventing a too big discrepancy between the model and the real cavity.

The chronology of the tuning of these 3 devices is being tested on our cold-model.

## 6 ACKNOWLEDGMENTS

The authors want to thank : Oliver Delferrière for his fruitful contribution to the 3D simulations of the dimensions of the end region (end plates tuning aspect), Jacques Gaiffier for his active participation to the experimental tests and mechanical design of the RFQ cold-model.

## 7 REFERENCES


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