A NEW RFQ MODEL APPLIED TO THE LONGITUDINAL TUNING OF A SEGMENTED, INHOMOGENEOUS RFQ WITH HIGHLY IRREGULARLY SPACED TUNERS

François SIMOENS†, Alain FRANCE, Jacques GAIFFIER,
CEA SACLAY, 91191 Gif-sur-Yvette, FRANCE

Abstract

The mathematical model that will be used for the final tuning of the High Intensity Proton Injector (IPHI) has been experimentally tested for several configurations of the aluminum IPHI cold model. The formalism takes in account the electromagnetic specific characteristics of the IPHI RFQ: this line is segmented, inhomogeneous, and the slug tuners are highly irregularly spaced. For all the tested configurations, the tuning procedure with plungers requires only a small number of iterations, and convergence is demonstrated on every electromagnetic parameters to be tuned.

1 INTRODUCTION

The new RFQ tuning formalism [1] that we have developed is based on:

- An electrical equivalent model that respects the electromagnetic behaviour of this cavity. This model allows to consider transverse and longitudinal disequilibria at the same time.
- A complete and rigorous mathematical analysis.

This paper presents the experimental tests made on our cold-model that validate this formlism.

2 IPHI RFQ ELECTROMAGNETIC PARAMETERS

2.1 Slug tuners function

To tune the IPHI RFQ electromagnetic parameters several devices are to be adjusted at different steps of machining and assembling. In particular, the 128 slug tuners distributed along this 8-m long cavity are used to tune:

1- The accelerating mode frequency $f_Q = 352,2\ MHz$

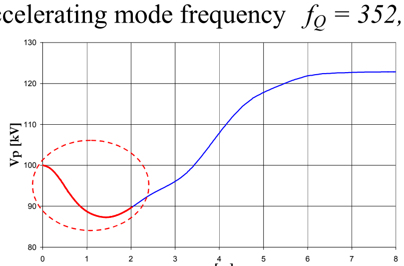


Fig. 1: Nominal IPHI voltage profile $V_p(z)$.

2 - A variable profile of the quadrupole component of the accelerating voltage $uQ(z)$ with a relative error w/r to the nominal profile $V_p(z)$ (Fig. 1) smaller than $\pm 10^{-2}$.

3 - The minimization of the dipole components named $uS(z)$ & $uT(z)$ of the accelerating voltage such that $|uD(z)/uQ(z)|<10^{-2}$, where $D=S$ or T.

2.2 IPHI RFQ electromagnetic specificities

Our formalism takes into account 3 specificities of the IPHI RFQ :

1- **Segmentation**: its line is divided into four 2-m long segments, with capacitive couplings in-between.

2- **Inhomogeneity**: the electrical parameters of the RFQ line continuously vary from one end to the other. The transverse resonance frequency of the cells (Fig. 2) evolves along the structure in order to pre-tune the IPHI voltage law [2].

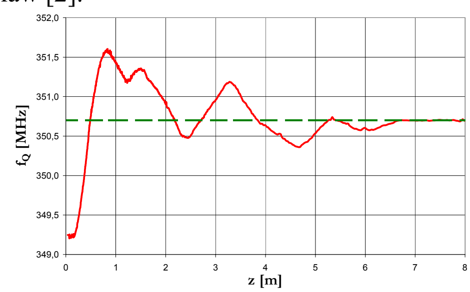


Fig. 2: Cells resonance frequency evolution along z.

3- **Highly irregularly spacing of the tuning slugs** along the structure: they are placed between vacuum windows, RF wave-guide inputs and cooling ducts.

2.3 Tuners commands computation principle

The 4 quadrants voltages distributions, measured with the bead-pull bench [3], are expanded on a set of continuous 'voltage base functions'. These functions are solutions of the eigen problem associated to the perfect RFQ model. The quadrupole ($cQ(i)$) and dipole ($cS(j)$ & $cT(k)$) modal coefficients reflect the discrepancy between the real measured RFQ and the ideal one:

$cQ(1)=1$ when f_Q is tuned.

$cQ(i)_{i>1} = 0$ when $uQ(z) = V_p(z)$

$cS(j)$ & $cT(k) = 0$ when the dipole disequilibria is compensated.

These field perturbations are transformed into inductance perturbations in an associated continuous base, with a one-to-one correspondence between the two sets. Then these continuous inductance perturbations functions are converted into tuners commands applying an original anti-aliasing filter to yield a stable convergence.

At the end of the analysis, our tuning code "rfqtunetool" generates 3 arrays of plungers displacements: one for the $cQ(i)$ quadrupole components

†fsimoens@cea.fr

command, and two for the 2 *cS(j) & cT(k)* dipole components tuning.

Expressed in mm, a positive value means that the tuner must be pushed towards the beam axis, a negative value outwards. The operator selects the modal components that he wants to tune simultaneously and the code computes the correspondent linear combination of the cumulative command.

One tuning iteration consists in the bead-pull measurement, the data analysis by our code and the displacement of the tuners. The tuning is achieved with a 0.01 mm final precision of the slug tuners depths.

3 EXPERIMENTAL RESULTS

The tuners commands have been successfully tested for many configurations of the cold model that have been progressively complicated. For each test, only plungers have been used starting from a flush position (neither the plate thickness nor dipole stabilizers rods have been adjusted).

The cold-model is equipped with removable electrodes:

- A first set of vanes with constant transverse section configures a homogeneous RFQ.
- Modulated electrodes (Fig. 3) and specific end plates can be mounted in the cold-model to assemble the exact first segment of the IPHI RFQ (same profile, same end regions). This RFQ is inhomogeneous.

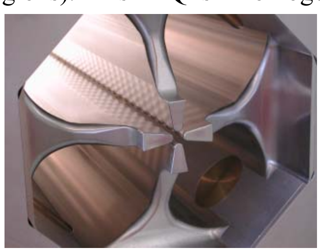


Fig. 3: modulated vanes mounted in the cold-model

3.1 1-m long RFQ tuning from E and H fields measurement

A flat voltage profile has been tuned in a 1-m homogeneous RFQ with eight tuners per quadrant. Specifically for this test, the commands have been computed from Electric (Fig. 4) or Magnetic field perturbation measurements. Tuning has been reached within 3 iterations. It shows its independence of the nature of perturbed field in the RFQ.

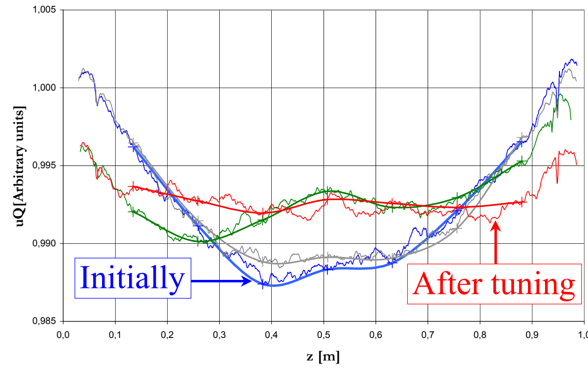


Fig 4: *uQ(z)* tuning deduced from a E-field perturbation

3.2 Two-meter long RFQ

A constant and a variable voltage profiles have been tuned in a homogeneous 2-m long RFQ (Fig. 5) :

- segmented with a capacitive coupling cell at mid-position.
- Having continuous electrodes on the total length.

The 2 first meters (red curve on Fig. 1) of the IPHI voltage profile have been chosen for this test since they offer the biggest variations of amplitude and second order derivative.

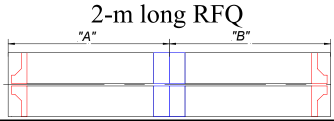
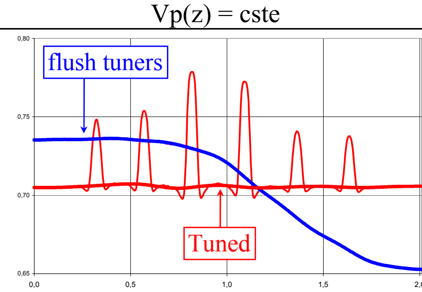
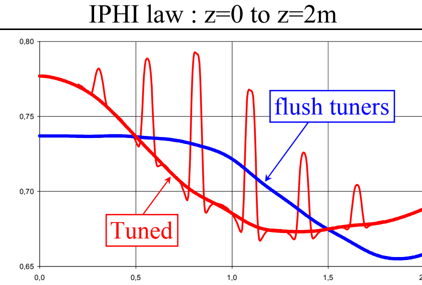
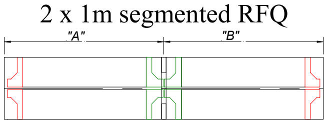
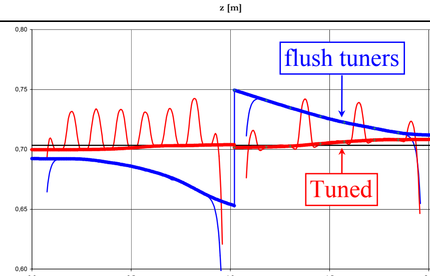
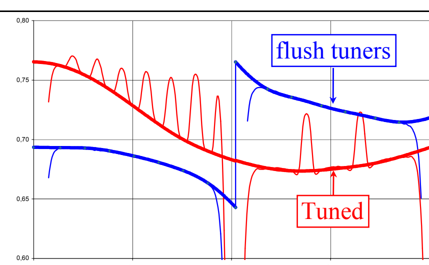
	Constant voltage profile Vp(z) = cste	Variable voltage profile IPHI law : z=0 to z=2m
 2-m long RFQ 		
2 x 1m segmented RFQ 		

Fig. 5: different configurations and voltage profiles that have been tuned in the 2-m long RFQ cold-model

The IPHI last test, which inherited all previous process improvements, has shown the convergence of all the parameters within 2 iterations (Fig. 6). The normalized quadrant voltages errors, that accumulates the quadrupole and the dipole errors, are smaller than 7.10^{-3}.

3.3 Two-meter long inhomogeneous RFQ segment

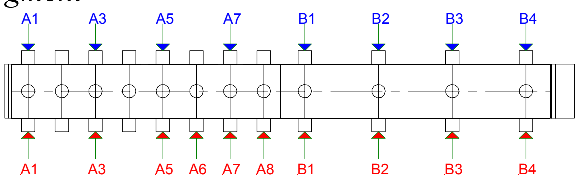


Fig. 7: Regular and irregular tuners distributions

Eight tuners are present on the first meter and four on the second meter (Fig. 7). The convergence of the modal components has been observed either for a regular or an irregular tuners distribution (Fig. 8). It validates our new method that assures the stability of the convergence whatever the tuner distribution is.

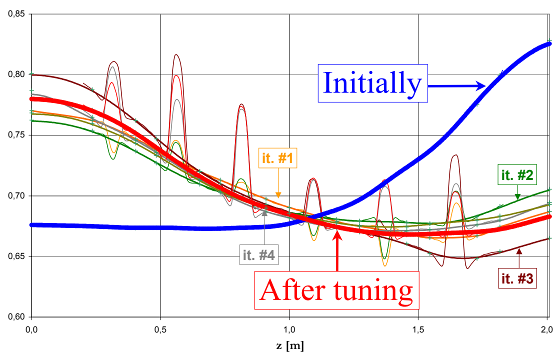


Fig. 8: uQ(z) tuning in a inhomogeneous RFQ segment

4 CONCLUSION

For all configurations, the tuning procedure requires only a small number of iterations (the IPHI RFQ has 128 slug tuners) and convergence is demonstrated on every component of functional bases that command individually the electromagnetic parameters. It has been demonstrated in many configurations of RFQs:

- With a constant or variable inter-electrode r_0
- With modulated or not electrodes
- Homogeneous or inhomogeneous (i.e. with a variable transverse section frequency)
- Segmented or not
- With a constant or variable voltage law
- At different resonance frequencies of the accelerating mode
- With different lengths.

These test have shown the interests of a complete and rigorous mathematical model: a fast convergence, a high precision tuning level and the possibility to apply our procedure to other RFQ's.

5 REFERENCES

[1] F. Simoens, A. France, "Theoretical Analysis of a Real-life RFQ Using a 4-Wire Line Model and the Spectral Theory of Differential Operators", this conference (EPAC 2002 Paris).

[2] P. Balleyguier, "3D Design of the IPHI RFQ Cavity", LINAC 2000 conference

[3] F. Simoens & al., "A Fully Automated Test Bench for the Measurement of the Field Distribution in RFQ and Other Resonant Cavity", this conference.

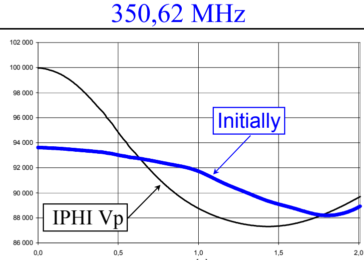
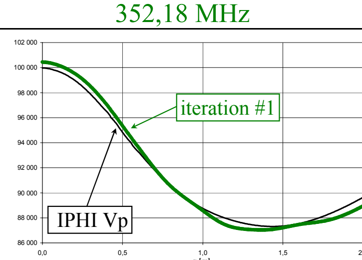
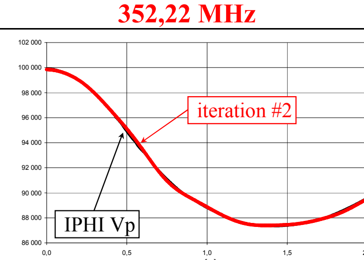
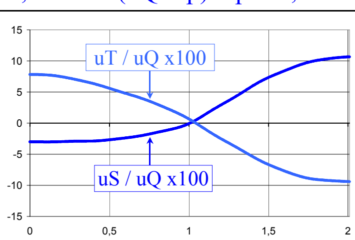
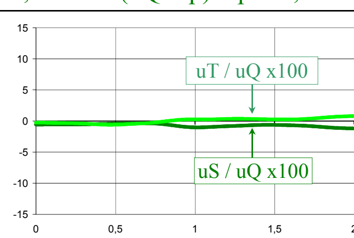
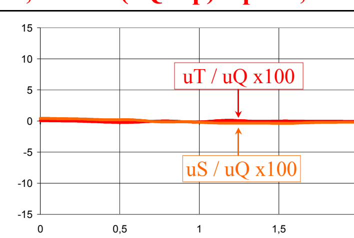
	Initially	After the 1st iteration	**After the 2nd iteration**
fo	350,62 MHz	352,18 MHz	**352,22 MHz**
uQ(z)	 $-6,4.10^{-2} < (uQ-Vp)/Vp < 3,4.10^{-2}$	 $-0,8.10^{-2} < (uQ-Vp)/Vp < 0,6.10^{-2}$	 **$-0,2.10^{-2} < (uQ-Vp)/Vp < 0,3.10^{-2}$**
uS(z) *uT(z)*	 $-9,4.10^{-2} < uD/uQ < 10,6.10^{-2}$	 $-1,2.10^{-2} < uD/uQ < 0,8.10^{-2}$	 **$-0,4.10^{-2} < uD/uQ < 0,4.10^{-2}$**
Ui	$-9,9.10^{-2} < (Ui-Vp)/Vp < 9,6.10^{-2}$	$-2,4.10^{-2} < (Ui-Vp)/Vp < 1,4.10^{-2}$	**$-0,7.10^{-2} < (Ui-Vp)/Vp < 0,7.10^{-2}$**

Fig. 5: simultaneous convergence of all the electromagnetic parameters within 2 iterations in a 2-m long RFQ