

# REVERSE ENGINEERING ON IPHI RFQ

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## Abstract

The Radio Frequency Quadrupole (RFQ) for the High-Intensity Photon Injector (IPHI) project has been designed and manufactured in the early 2000s. It is now operating at CEA Saclay since 2016 and accelerates a 100 mA continuous beam up to 3 MeV. It is a 6-meter-long, 3 segments vane RFQ, with 352.2 MHz operation frequency and non-constant voltage profile. From this RFQ, a lot of experience has been gained, and based on this feedback, other RFQ were designed by the CEA, such as the one for SPIRAL2, LINAC4, or ESS, which are now operating. For maintenance purposes and to simulate the changes before we operate them, a new Virtual 3D Model (VM) has been developed. This model is simplified and may have the same RF performances as the existing one. This paper presents this new model.

## INTRODUCTION

The RFQ for IPHI was the first operated at CEA [1]. The methodology for the design, measurement, and tuning is based on a Transmission Line Model (TLM) presented in [2]. To compensate for manufacturing errors on the vanes and adjust the operating frequency, 96 slug tuners with specific lengths were inserted in the RFQ in 2013. During the conditioning, in 2015, RF seals have been damaged on two RF ports, the replacement induced a 10% error on the voltage profile. A correction of this voltage profile is today (2023) investigated but a preliminary study is mandatory. The simulation tools used in the early 2000s to calculate the electric parameters and estimate the thermo-mechanical deformation were MAFIA and SUPERFISH. New tools, more efficient, are now available and new simulations, based on a new virtual model (VM), presented in this paper, will be performed to estimate the impact of future maintenance operations such as tuning, to minimize the number of tuner replacements.

## RFQ CROSS SECTION

The beam is focused along the RFQ via the transverse electric field of the TE<sub>210</sub> mode. It is bunched and accelerated via a longitudinal electric field generated by the vane modulations. For simplification purposes, for the VM, we were only interested in the RF performances, and we did not consider the beam dynamics of the cavity. Therefore, we neglected the vane modulation. The transverse electric field amplitude is set by the inter-vane voltage which profile depends on the variation of the quadrant cross-section. This cross-section defines a TLM with capacitances and inductances. The comparison between the VM and the actual physical model cross-section is presented in Fig. 1. For the VM, the vanes are straight and the Montgolfier shape is replaced by a square with rounded corners. Three geometrical parameters of the VM,  $r_0$ ,  $y_{j1}$ , and  $y_{j3}$ , are optimized to get

similar electrical parameters to the TLM of the real model. The voltage profile of the VM is compared to the expected voltage profile in Fig. 2. The overall difference is lower than 5% and can be easily corrected by the insertion of a few millimeters for some tuners.

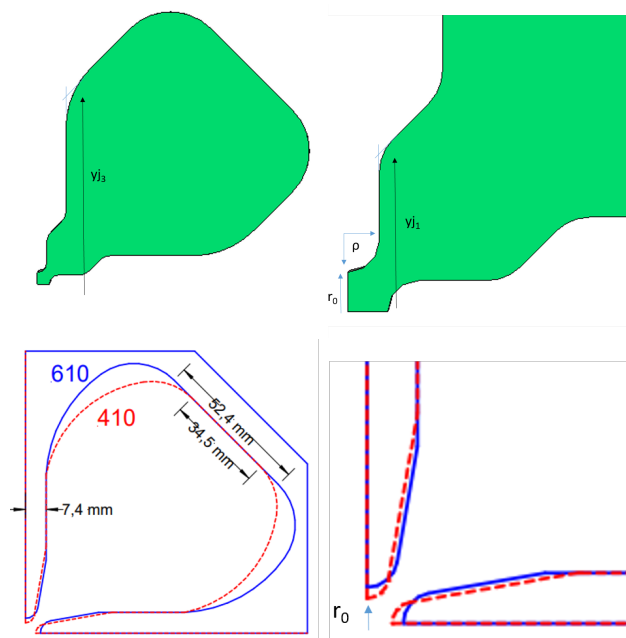


Figure 1: RFQ cross section. Top: Virtual model ; Bottom: Real model. Left: Overview; Right: Zoom on the vane.

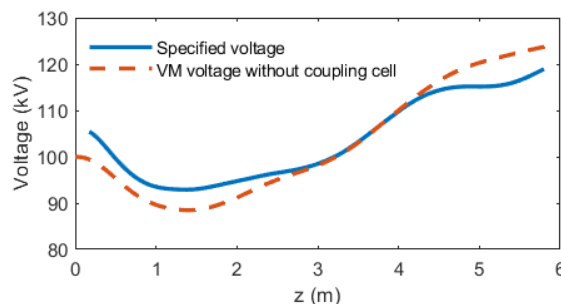


Figure 2: IPHI inter-vane voltage profile.

## COUPLING CELL

### RFQ Stability

The stability of a RFQ is related to the frequency distance between the TE<sub>210</sub> accelerator mode and the closest dipolar mode. The longer is the RFQ the shorter is this frequency distance. IPHI being a 6-meter long RFQ, its stability was a concern during its design and therefore it was decided to divide it into 3 segments, connected via 2 coupling cells; the

first one at  $z = 2$  m and the second one at  $z = 4$  m. Dipolar modes frequencies depends also on the logarithmic voltage slope  $S_D = 1/V * \partial V / \partial z$  at the RFQ extremities which are fixed by the vane undercut geometries. The frequency separation, regarding the RFQ length and the boundary conditions  $S_D$  of the dipolar modes is presented in Fig. 3. The segmented RFQ is as expected more stable. Nevertheless, for a 6-meter long RFQ, the gain is not obvious and for the RFQ designed at CEA after IPHI, non-segmented RFQ were preferred, to avoid the difficulties to tune properly the coupling cells. For these more recent RFQ the efforts were pushed on the optimization of the  $S_D$  parameter, by adjusting the vane undercut geometries at the RFQ extremities.

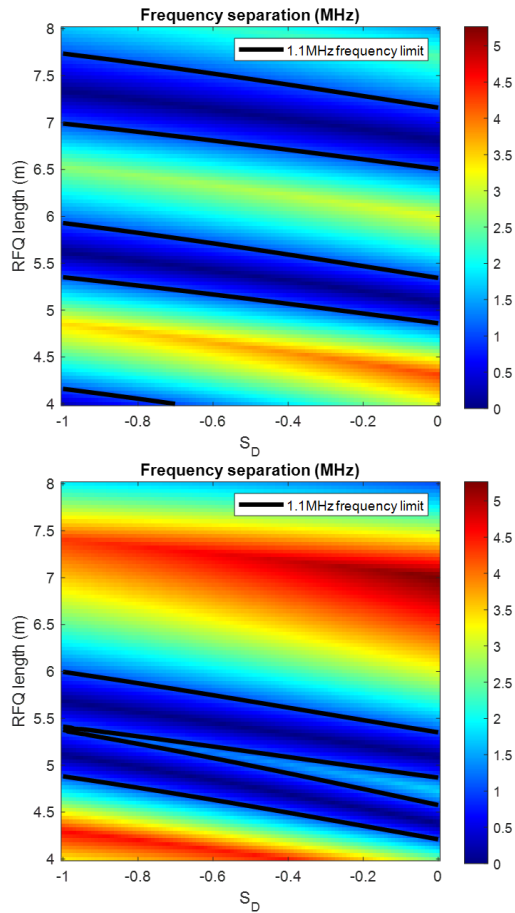


Figure 3: RFQ stability. Top: without coupling cell ; Bottom: with two coupling cells.

### Coupling Cell Characterisation

In the TLM, voltage-slope ( $\partial_z U_{Q+}$  before and  $\partial_z U_{Q-}$  after the coupling cell) are assumed to depend almost exclusively on voltage ( $U_{Q+}$  before and  $U_{Q-}$  after the coupling cell), according to :

$$\begin{pmatrix} \partial_z U_{Q-} \\ -\partial_z U_{Q+} \end{pmatrix} = \begin{pmatrix} s_e^- + s_c^- & -s_c^- \\ -s_c^+ & s_e^+ + s_c^+ \end{pmatrix} \begin{pmatrix} U_{Q-} \\ U_{Q+} \end{pmatrix}$$

The coupling cell is then characterized by the parameters  $s_e^-$  and  $s_e^+$ , related to the even mode and  $s_c^-$  and  $s_c^+$  related to the odd mode.

### Coupling Cell Geometry

The 6 geometrical parameters optimized for the coupling cell are presented on Fig. 4. Seven hundred configurations of a 1-meter-long RFQ, with a coupling cell at  $z = 0.5$  m were simulated on CST eigenmode solver. For each simulated configuration, the inter-vane voltage at 6 positions ( $z = 0$  m,  $z = 0.1$  m,  $z = 0.3$  m,  $z = 0.7$  m,  $z = 0.9$  m and  $z = 1$  m) are extracted for the first odd ( $0 + 0$ ) and even ( $0 - 0$ ) quadrupolar modes. A quadratic extrapolation aims to estimate the inter-vane voltages and slopes for these modes at the cell position,  $z = 0.5$  m. Then the parameters  $s_e^-$ ,  $s_e^+$ ,  $s_c^-$  and  $s_c^+$  are extracted solving the equation :

$$\begin{pmatrix} \partial_z U_{Q-}^e \\ \partial_z U_{Q-}^o \\ -\partial_z U_{Q+}^e \\ -\partial_z U_{Q+}^o \end{pmatrix} = \begin{pmatrix} U_{Q-}^e & U_{Q-}^e - U_{Q+}^e & 0 & 0 \\ U_{Q-}^o & U_{Q-}^o - U_{Q+}^o & 0 & 0 \\ 0 & 0 & U_{Q+}^e & U_{Q+}^e - U_{Q-}^e \\ 0 & 0 & U_{Q+}^o & U_{Q+}^o - U_{Q-}^o \end{pmatrix} \begin{pmatrix} s_e^- \\ s_c^- \\ s_e^+ \\ s_c^+ \end{pmatrix}$$

The configurations providing the best fit were finally used for the coupling cell of the VM. The end circuit at  $z = 0$  m and  $z = 6$  m were replaced by a simple perfect magnetic conductor wall.

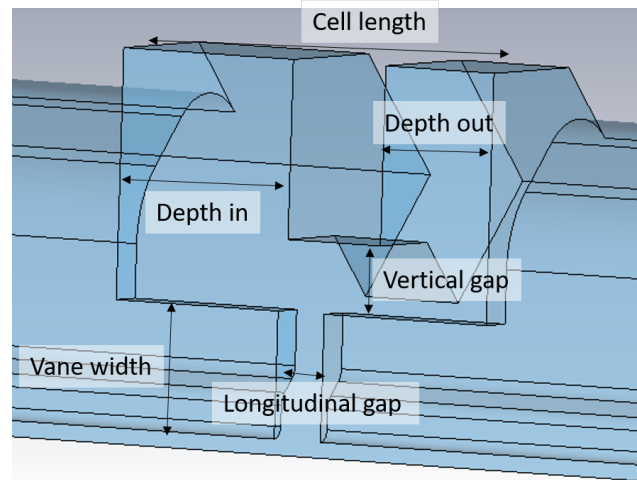


Figure 4: Coupling cell geometry.

## FINAL VIRTUAL MODEL

The final VM is presented in Fig. 5. To reduce the simulation time, but allow the existence of dipolar modes, two quadrants are modeled.

The VM is tuned via 96 slug tuners (8 tuners per section per quadrant) and 4 rectangular blocks, corresponding to the RF couplers. The tuning process is described in [3]. The estimation of the boundary conditions for the dipolar modes ( $S_D$  parameters) was critical for the convergence of

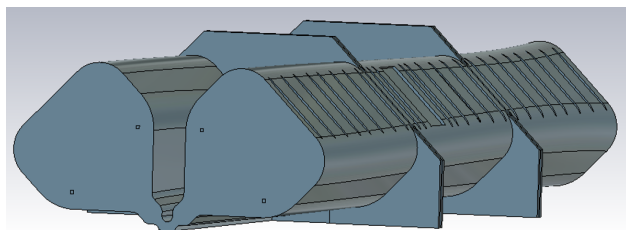


Figure 5: Final Virtual Model geometry.

the tuning process. Two tunings were performed: for the first one the tuners were adjusted to get the same voltage profile as the one measured during the last bead pull, in June 2022; for the second one, we corrected this voltage profile, to get the nominal voltage defined initially.

### First Tuning

For the first tuning, the command for the voltage profile is the one measured in June 2022. After 4 iterations, we obtained the voltage presented in Fig. 6. The results are close to the command, within a range of 4% for the quadrupolar mode.

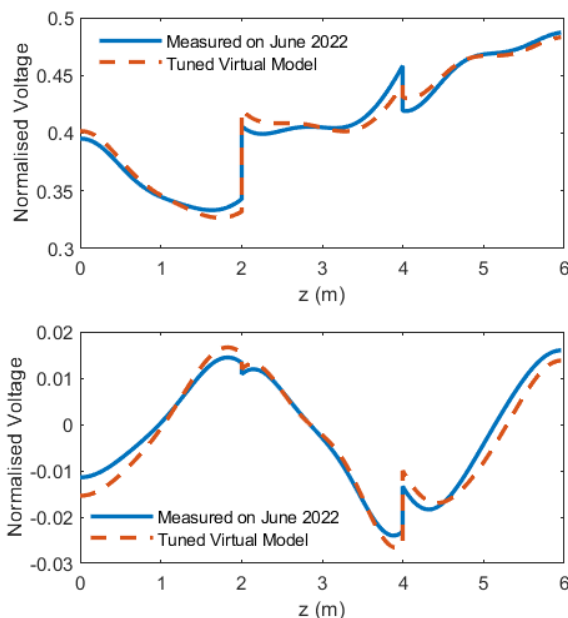


Figure 6: First tuning of the VM, the command corresponds to the measure on June 2022 Top: Quadrupolar mode; Bottom: Dipolar mode.

### Second Tuning

Starting from the configuration corresponding to the voltage profile measured on the real RFQ in June 2022, a second tuning is performed, using the nominal voltage profile as

the command. After 3 iterations the voltage profile presented in Fig. 7 is achieved. The accuracy is about 2.5% in quadrupolar mode and 0.5% in dipolar mode. This validates the convergence of the tuning procedure on the VM.

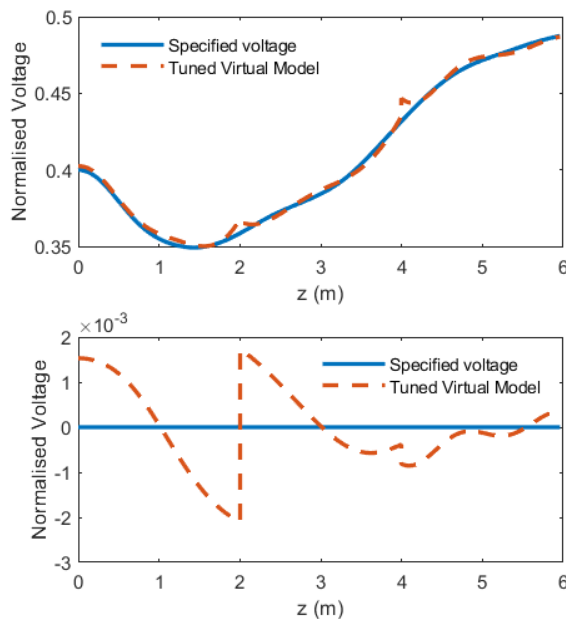


Figure 7: Second tuning of the VM, the command corresponds to the specified voltage. Top: Quadrupolar mode; Bottom: Dipolar mode.

## CONCLUSION

A Virtual Model for the IPHI RFQ has been presented. Its RF performances fit well with the real RFQ. It can be adjusted to correspond to the actual RFQ and a tuning process can be simulated, to expect the performances after a new tuning on the real model. This model may help us to identify the tuner displacements which are the most relevant to correct the voltage profile, and so to reduce significantly the number of tuners used for the next tuning.

## REFERENCES

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