A New RF Tuning Method for the End Regions of the IPHI 4-vane RFQ

O. Delferriere, M. Desmons, A. France, R. Ferdinand

A NEW RF TUNING METHOD FOR THE END REGIONS OF THE IPHI 4-VANE RFQ

O. Delferrière, M. Desmons, A. France, CEA-Saclay,
DSM/DAPNIA/SACM, 91191 GIF-Sur-Yvette, France
R. Ferdinand, GANIL, Boulevard H. Becquerel, F - 14076 Caen

Abstract

The 3-MeV High Intensity Proton Injector (IPHI) RFQ is the assembly of three 2-m long coupled-segments. The tuning of the end regions of such accelerator with respect to the quadrupole mode, is generally made by machining the thickness of the end plates or increase of the notch in the vanes (LEDA). The dipolar modes are adjusted around the accelerator quadrupolar mode by adding dipole rods on the end plates and adjusting their length. In the case of the last IPHI RFQ segment, the achievable tuning range obtained with the possible plate thickness was not sufficient to adjust the frequency at 352 Mhz without modifying the notch depth, leading to serious engineering problem for the cooling, new thermo-mechanical simulations and drawings. To avoid these difficulties, a new way has been investigated. The end plate thickness adjustment is replaced by a “quadrupole rod” –as opposed to the "dipole rod" - length adjustment. These rods are situated between the beam axis and the dipole rods, and the tuning range is largely increased. The paper will describe this method applied to the IPHI RFQ and some experimental results obtained on the cold model.

INTRODUCTION

Over the last years, the two French national research agencies (CEA and CNRS) have undertaken a large research program in order to study and construct a prototype of the low energy part of a High Power Proton Accelerator (HPPA). A large domain of applications is concerned, such as for example spallation neutron sources, Accelerator Driven Systems (ADS) for nuclear waste transmutation, production of radioactive ion beams, neutron production (IFMIF) or neutrino and muon factories. The main objective of this project is to have technological, industrial and experimental references, to master the conception of such a machine and its further operating.

The IPHI [1] demonstrator (Injector of Protons for High Intensity beams) has to deliver beams of several tens of MW. It originally consisted in the ECR ion source SILHI which delivers more than 100 mA CW at 95 keV, a LEBT for matching the beam to the RFQ to reach 5 MeV beam energy, and followed by a 10 MeV DTL.

The funding difficulties encountered in years 2002 and 2003 led us to redefine the characteristics and the performances of the accelerator. The main change concerns the output energy of the RFQ cavity which has been limited to 3 MeV. The nominal intensity is maintained at 100 mA in CW mode. The construction the Drift Tube Linac to increase the energy from 5 to 10 MeV is abandoned.

3 MEV RFQ PARAMETRERS

The present design of the RFQ comprised 6 sections of 1 meter long each assembled in 3 segments separated by coupling plates [2].

Table 1: IPHI RFQ parameters

Structure	4 vanes
Frequency	352.2 MHz
Total length	6 m, (6 one meter sections)
Resonant coupling plate	2 (3 coupled segments)
Vane voltage	87 to 123 kV (Kp ≤ 1.7)
Output energy	3.02 MeV
Theoretical transmission	99.1 % (accelerated)
Beam power	300 kW
Max total power	1200 kW (two 1.3 MW klystrons)

RFQ END DETUNING

When the 3-MeV energy has been fixed for the final RFQ design at 6 meters, the study of the Crandall cell was performed only from the beam dynamics aspect. The RF aspect was forgotten. During the fabrication procedure, when the pre machining of each section had to be done at *Mécachrome* (French company), we discover that the adjunction of the end vane profile will eliminate a large part of vane copper (Fig. 1), resulting in 2 major consequences: First, there is not enough plane surface in front of the vane to put locating for vane alignment measurements; Second, much more sensitive, the gap between the vane and the end plate was increased from 8.1 mm to 14.17 mm, rising the local frequency up to 364.7 MHz.

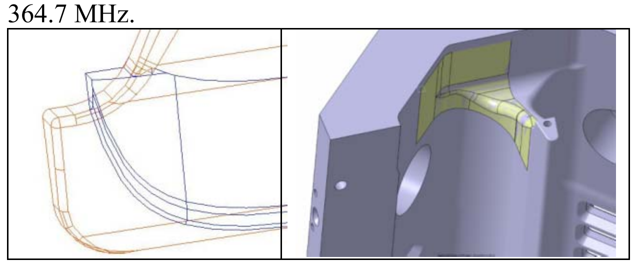

Figure 1: IPHI 6-meter section vane end profile modification.

The tuning of the IPHI end region, with respect to the quadrupole mode, is made by machining the thickness of the ending plate. In this particular case, the end region tuning became out of range. The frequency was too high, even if the plate thickness was completely eliminated.

QUADRUPOLE RODS

To face this tuning problem, several studies were made to lower the frequency. The first one was to make the notch deeper by about 6 mm which is just equal to the thickness of copper between the cooling channel and the vane end (Fig. 2). This solution was eliminated due to major modifications in the drawings, with additional thermo-mechanical calculations, which was incompatible with the fabrication schedule. On possibility was to add rings in front of the vane noses which would also lower the frequency, but the resulting smaller gap, less than the inter vane one, was not acceptable regarding the electric field peak.

Finally the adopted solution consists in adding "quadrupole rods" between each vane in the 4 quadrants, situated between the beam axis and the dipole rods (Fig. 3).

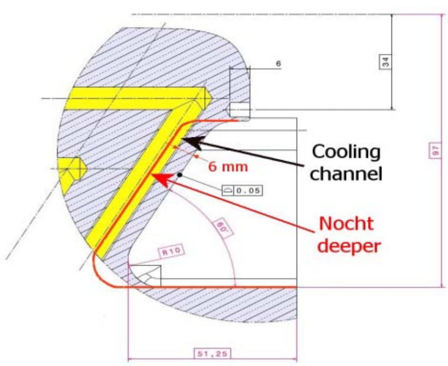

Figure 2: IPHI vane end profile and cooling channel.

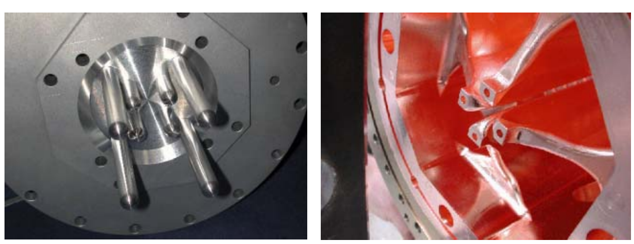

Figure 3: End plate with DR and QR, and vane ends.

3D SIMULATION WITH SOPRANO

A set of 3D Model have been built to study the RFQ 6th segment, by using CAD program I-DEAS. Each model is 150 mm length with standard planar ending plate, and with dipole rods (DR) and quadrupole rods (QR) of adjustable length. The cavity bottom is assumed constant. The mesh with tetrahedral shape is done with I-DEAS and a dedicated interface allow transferring the model and calculating the frequency modes with SOPRANO-EV [3].

Length of DR was preliminary fixed to 125 mm to lower the first dipole mode frequency below 352 MHz. The frequency of the monopolar mode localized at the RFQ extremity, also named "rod mode" [4], is also pushed below 352 MHz.

Rods length had to be adjusted in order to tune the cavity and optimize the mode frequencies. As the influence of each kind of rods is coupled to the other, we have to find a set of values by adjusting first the QR length and then the DR length and iterate the process to reach an optimal condition. As we can see on table 2, a good adjustment has been achieved with 120 mm length DR and about 25 mm length QR. The dipolar and monopolar mode frequency are about 20 Mhz and 12 MHz below the accelerator mode respectively.

Table 2: SOPRANO rod length optimization

Rods length (mm)		Frequency modes (MHz)		
Dipole	Quadrupole	Monopole	Dipole	Quadrupole
0	0	764.05	374.47	358.1
100	0	407.02	360.37	358
100	20	373.9	350..5	354.06
100	40	324.7		345.3
120	**20**	**345.3**	**344**	**354.31**
120	30	326.4	336	350.0

A more sophisticated model (Fig. 4) has been built to study the complete segment by using a 64 bit-LINUX version of SOPRANO, temporarily lent by *Vector-Fields*. It includes half the segment assuming tangential E field at the middle of the segment, the ending plate with its 4 dipole rods and 4 quadrupole rods, and also the modulation of the vanes. We have chosen the tuning corresponding to DR and QR lengths of 120 mm and 20 mm respectively. We observe a frequency decrease for both quadrupolar (-5.5 MHz) and dipolar (-10.5 MHz) frequency, due to the model length and to the presence of vane modulations (Table 3). The frequency shift is only of -1 MHz for the monopolar mode. Further simulations are needed, especially with the same model but without modulation to determine the frequency shift origin. An intermediate 500 mm length model gave f_Q=351.78 MHz, f_D=341.18 MHz, and f_M=344.31 MHz.

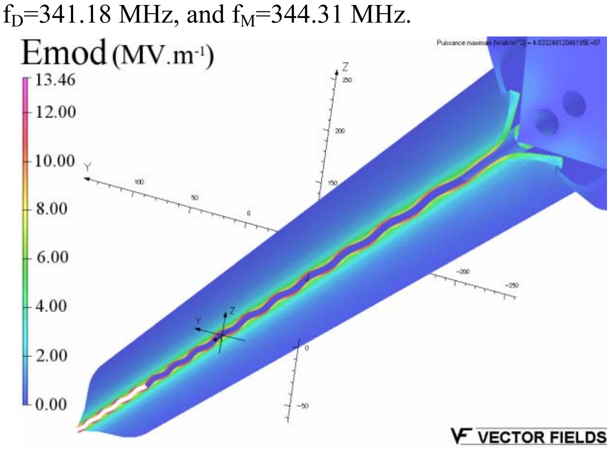

Figure 4: ¼ of IPHI 6th segment simulation with SOPRANO.

Table 3: SOPRANO eigen frequencies for rod lengths L_{dipole}=120 mm ϕ=16 mm and L_{quad}=20 mm ϕ=16 mm

Mode	Quadrupole	Mode	Dipole	Mode	Monopole
Q0	**348.83**	D0	**335.44**	M	**344.37**
Q2	383.04	D2	367.48		
Q4	468.98	D4	442.30		
Q6	585.13	D6	601.65		
Q8	716.92	D8	718.43		

The maximum power density deposition in the cavity is about 115 W.cm^{-2}, and situated on the vane ends. Power density of 25 W.cm^{-2} and 18 W.cm^{-2} are observed respectively on the DR and QR (Fig. 5). The total power dissipated in the rod is 606 W for the DR and 149 W for the QR.

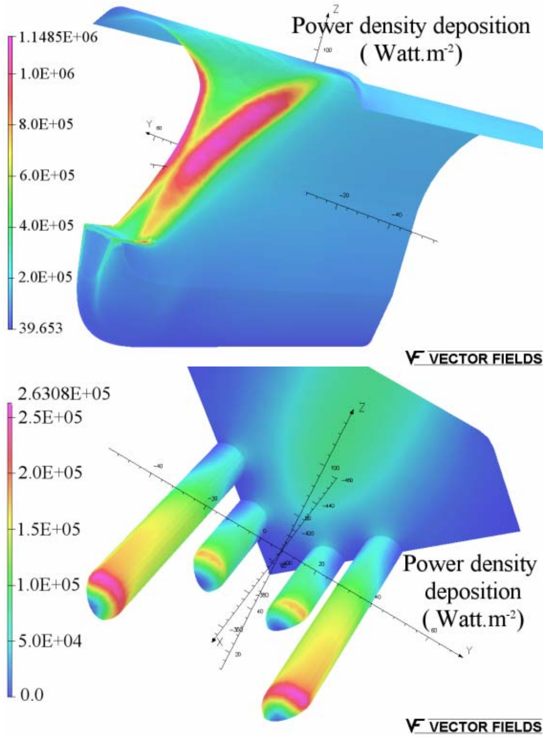

Figure 5: Power density deposition on vane and rods.

COLD MODEL EXPERIMENTAL RESULT

The last segment of the IPHI cold model has been used to validate numerical simulations. This segment is 2.0155 m long, bounded by a coupling-plate at one end, and an end-plate at the other. Free-space radiation at the unpaired coupling end turns out to be neglectable, at least for lower modes. Coupling-plate geometry was held constant (155 mm DR, 9 mm adjustable thickness), and end-plate QR and DR lengths were varied. Simulated (Table 2) and measured (Table 4) frequencies are then used to derive "intrinsic" boundary condition numbers, which might compare to each other.

Table 4: Measured eigen-frequencies (MHz) vs. end-plate rod lengths (mm). End-plate adjustable thickness set to 0

L_{DRod}	L_{QRod}	D_0	Q_0	L_{DRod}	L_{QRod}	D_0	Q_0
120	10	339.30	348.45	141	20	338.25	348.30
130	10	339.15	348.45	120	30	338.25	348.00
141	10	338.85	348.45	130	30	337.80	348.00
120	20	338.85	348.30	141	30	337.05	348.00
130	20	338.70	348.30				

It may be shown that each segment end is fully characterized by its "end detuning parameter" H, equal to the product segment length × frequency detuning (with respect to open-circuit condition). No attempt has been made to derive absolute values of H for the cold-model; rather we consider tuning slopes $\Delta H/\Delta L_{Rod}$, which are in fact required for subsequent RFQ tuning.

First note that the hemispherical cap at rod end makes Δf strongly non-linear (*) for low rod length values, both in simulations (Table 5) and experiments (Table 6); this region is however not representative, since real-life tuning would consist in small variations about an average rod length. As expected, measured Δf_{Q0} is virtually not dependant on DR length; this is apparently not exactly the case in simulations, probably owing to the small length of model. Simulations and measurements are in reasonable agreement every time comparison is possible. For DR length in the 20~30 mm range, tuning slopes are close to –60 and –120 m.kHz/mm for Q_0 and D_0 modes respectively. For comparison, with end plane tuning method, the tuning slope for Q_0 is about +26 m.kHz/mm, that is to say, +1 mm of tuning plate ≡ -0.4 mm of QR.

Table 5: Tuning slopes derived from simulation. L in mm, Δf in kHz, ΔH in m.kHz, ΔH/ΔL in m.kHz per mm

L_{DRod}	L_{QRod}	Δf_{Q0}	ΔH_{Q0}	$\Delta H_{Q0}/\Delta L_{QRod}$
100	0 ~ 20*	–3940	–591	**–29.6**
100	20 ~ 40	–8760	–1314	**–65.7**
120	20 ~ 30	–4310	–646.5	**–64.6**
L_{DRod}	L_{QRod}	Δf_{D0}	ΔH_{D0}	$\Delta H_{D0}/\Delta L_{QRod}$
100	0 ~ 20*	–9870	–1480.5	–740.2
100	20 ~ 40	n/a	n/a	n/a
120	20 ~ 30	–8000	–1200	**–120.0**

Table 6: Tuning slopes derived from measurements

L_{DRod}	L_{QRod}	Δf_{Q0}	ΔH_{Q0}	$\Delta H_{Q0}/\Delta L_{QRod}$
120 to 141	10 ~ 20*	–150	–302	**–30.2**
120 to 141	20 ~ 30	–300	–604.6	**–60.5**
L_{DRod}	L_{QRod}	Δf_{D0}	ΔH_{D0}	$\Delta H_{D0}/\Delta L_{QRod}$
120	10 ~ 20*	–450	–907	–90.7
120	20 ~ 30	–600	–1209	**–120.9**
130	10 ~ 20*	–450	–907	–90.7
130	20 ~ 30	–900	–1814	–181.4
141	10 ~ 20*	–600	–1209	–120.9
141	20 ~ 30	–1200	–2418	–241.8

CONCLUSION

A new RF tuning method has been established for end region of IPHI RFQ. The experimental measurements obtained on the cold model have confirmed those given by FEM simulations with SORANO. We will soon take advantage of the 64 bit version of the code to improve the simulation results on the large model.

This new method is foreseen for the SPIRAL2 RFQ [5] at 88.05 MHz to simplify the end region tuning and increase the tuning range.

REFERENCES

[1] R. Ferdinand et al., “Status Report on the 5 MeV IPHI RFQ”, Linac 98, Chicago, August 1998.
[2] P-Y. Beauvais, “Recent evolutions in the design of the French High Intensity proton Injector (IPHI)”, EPAC 2004, Lucerne, July 2004.
[3] OPERA-3D code,© *Vector-Fields Ltd (UK).*
[4] P. Balleyguier, F. Simoens “Simulations vs. measurements on IPHI RFQ cold model”, EPAC 2002, Paris, June 2002.
[5] R Ferdinand et al., “SPIRAL2 RFQ Prototype -- First Results”, June 2006, this conference.