

THE RF DESIGN OF THE LINAC4 RFQ

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Abstract

In the Linac 4 and the SPL, a 3 MeV RFQ is required to accelerate the H⁺ beam from the ion source to the DTL input energy. While the 6-meter long IPHI RFQ was initially chosen for this application, a CERN study [1] suggested that a dedicated, shorter 3-meter RFQ might present several advantages. The 2D cross-section is optimized for lower power dissipation, while featuring simple geometrical shape suitable for easy machining. RF stability is evaluated using a 4-wire transmission model and 3D simulations, taking electrode modulation into account. The resulting RFQ is intrinsically stable and does not require rod stabilizers. End circuits are tuned with dedicated rods. RF power is fed via a ridged waveguide and a slot iris. Vacuum port assemblies are positioned prior to brazing to minimize RF perturbation. The 32 tuning slugs form a set of stable sampling, able to tune 9 modes. Tuner parameters are derived from bead-pull accuracy specification and fabrication tolerances. Signals delivered by pickup loops inserted in 16 of these tuners will be used to reconstruct the voltage profile under operation. Thermo-mechanical simulations are used to design temperature control specifications.

INTRODUCTION

The Linac4 RFQ must be capable of providing the Linac4 beam as the PS Booster injector, working at 1.1 Hz with 0.400 ms beam pulses, 70 mA beam current, or to feed the Linac4 when working with the SPL either as LHC injector (2 Hz, 1.2 ms, 40 mA) or as the neutrino factory driver (50 Hz, 1.2 ms, 70 mA). The RFQ will be of brazed-copper construction and will be built and assembled at CERN (Figure 1).

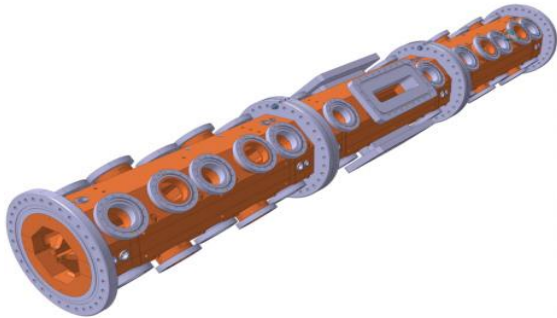


Figure 1: Linac4 RFQ

RF DESIGN

Cavity design

The 2D section of the RFQ cavity has been kept constant over the full RFQ length, in order to simplify the mechanical fabrication.

A loaded, lossless 4-wire transmission line model is used to relate differences between measured and desired inter-vane voltages (Figure 2) and to tune devices dimensions (end plates and slugs) [2]. The location of the quadrant bottom plane is adjusted for 345.53 MHz resonance frequency with tuner in zero position. Electrical parameters of 2D cross-section (without any tuner) derived from 2D COMSOL simulations are given in Table 1. The 346.020 MHz frequency anticipates tuner bore detuning.

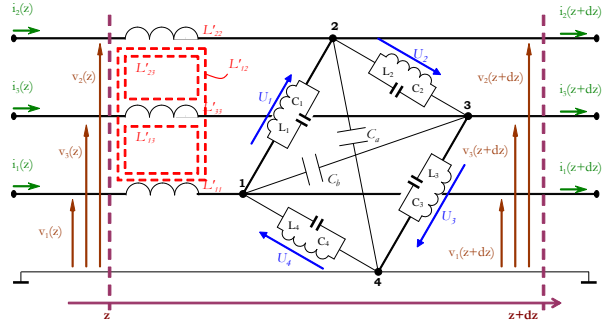


Figure 2: 4-wire line model

Table 1: Transmission-line parameters

Parameter	Value	Unit
parallel inductance	$6.970031 \cdot 10^{-9}$	H.m
parallel capacitance	$30.352946 \cdot 10^{-12}$	F/m
diagonal capacitance	$1.954868 \cdot 10^{-12}$	F/m
quadrupole eigen-frequency	346.020	MHz
dipole eigen-frequency	335.389	MHz

Table 2 reports the main electrical parameters for the RFQ cavity, computed for the dipole and quadrupole mode cut-off frequencies. The power dissipation is calculated assuming 5 mΩ surface resistance for copper.

Table 2: RFQ electrical parameters

Linac4 RFQ electrical parameters	quadrupole	dipole	Units
Vane voltage	78.27	78.27	kV
Quality factor	10269	9936	
Stored energy	0.372	0.395	J/m
Dissipated power	78.738	83.848	kW/m

Electric field (max)	30.860	35.312	MV/m
Kilpatrick	1.675	1.917	
Magnetic field (max)	5444	5595	A/m
Magnetic field (in J6)	5397	5550	A/m

Vane modulation effect

Electrical parameters (parallel and diagonal capacitance variations vs. abscissa along RFQ, assuming constant parallel inductance) of V2TERM modulated structure are estimated by COMSOL 3D simulation of each RFQ cell. Quadrupole and dipole frequency shifts (respectively -0.208MHz and -3.871MHz with respect to their values for un-modulated structure) are used to estimate Eigen-frequencies and voltage profile of modulated cells (Figure 3). Q-mode frequency shift and voltage difference should be easily cancelled by tuners.

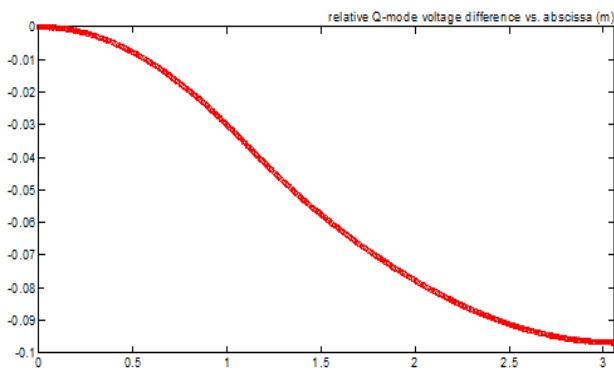


Figure 3: Relative Q-mode voltage difference vs. abscissa

VACUUM PORTS

Vacuum ports are arranged in arrays of diaphragms designed to attenuate the RF transmission into the vacuum system, but these openings lead an apparent increase of resonating volume. This increase can be compensated by carefully adjusting the position of port assembly in its RFQ opening. SOPRANO 3D simulations have been performed to estimate the optimum position of a port design (Figure 4). Furthermore, the port will be experimentally adjusted before second brazing in order to reduce mechanical defaults due to machining and first brazing.

END CELLS TUNING

The tuning of the end region, with respect to the quadrupole mode, is made by adjusting the length of 4 rods. 3D calculations with SOPRANO software have been performed (1) to optimize the diameter and position of the rod in order to minimize the electric field between rod and vane, (2) to optimize the tuning range of these rods and (3) to obtain the power deposition on both, the

vanes, the rod and the end plate, for thermal and mechanical simulations (Figure 5).

The study for the tuning of the end cells has shown that dipole rods are not required because the frequency separation between the accelerating quadrupole mode and the adjacent dipole modes is about 5 MHz, which should guarantee sufficient stability during operation.

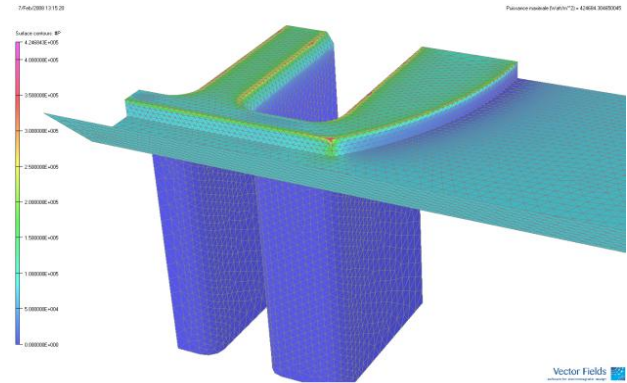


Figure 4: Vacuum port

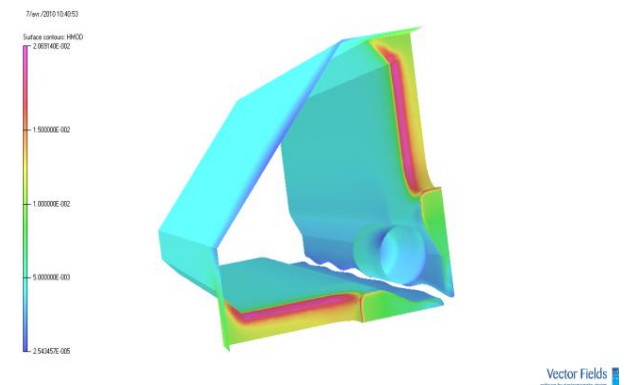


Figure 5: End cell with rod

TUNING STRATEGY

The tuning of the RFQ cavity will be assured by a set of 32 identical 80mm-diameter piston tuners plus the RF input coupler and the three RF dummy ports. (Figure 1) Tuner 2D inductance slope required by the RFQ transmission line model are derived from COMSOL 3D simulations. Different slug tuner positions have been examined, from -40 mm to +35 mm. The resulting linear frequency shift in [0, +35] shows that Slater's small perturbation theory may be applied safely in this case (Figure 6).

Tuner spacing is directly related to RFQ voltage tuning process [3]. Bead-pull measurements are used to sense longitudinal magnetic field $H_z(x_0, y_0, z)$ vs. abscissa z at some transverse location $\{x_0, y_0\}$ in RFQ quadrants, and a conversion factor $\kappa(z) = V(z)/H_z(x_0, y_0, z)$ is applied to recover the value of inter-vane voltage $V(z)$.

COMSOL 3D simulations has also shown that tuner spacing larger than 240 mm would yield relative variations of $\kappa(z)$ less than a few 10^{-3} .

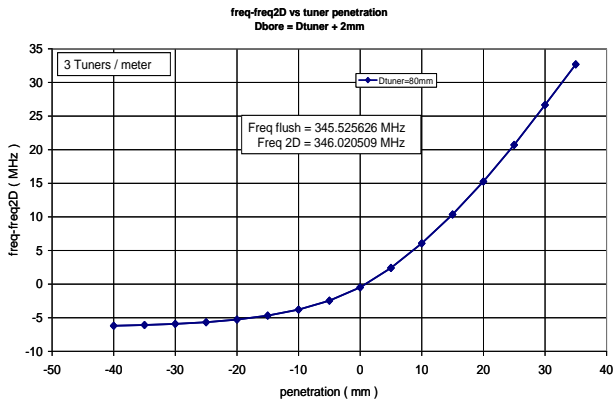


Figure 6: 3D frequency shift vs. tuner position

TUNER POSITION RANGE

Errors in the mechanical construction have an important impact on the electromagnetic behavior of the RFQ cavity. Once the construction of the RFQ module is achieved, these errors can be compensated by means of the slug tuners. Tuner position limits required to compensate for given construction errors may be derived from inter-vane capacitance errors. Tolerances on electrode tips are defined by the two numbers t and δ :

- center of curvature of each electrode tip is located in a square with side $2t$, centered at its theoretical location;
- electrode tip radius error is bounded by $\pm\delta$.

Present evaluation uses $t = 30 \mu\text{m}$ and $\delta = 10 \mu\text{m}$. Tuner positions are also used to compensate for C_{QQ} errors resulting from vane modulations. The resulting capacitance relative error volume is displayed in Figure 7. It is inscribed in a parallelepiped bounded by $\pm 2.293\%$ along the QQ axis, and $\pm 3.516\%$ along SQ and TQ axes.

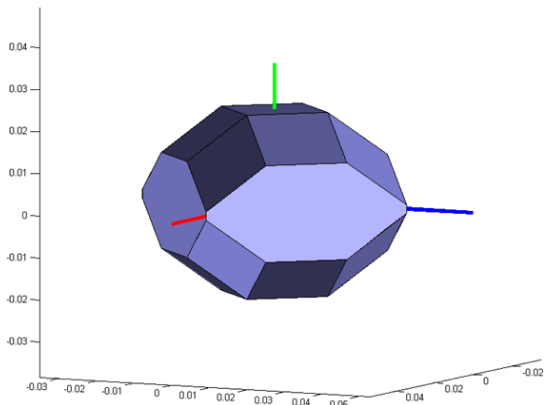


Figure 7: Capacitance relative error volume, in the $\{QQ,SQ,TQ\}$ basis

Tuner position range required for compensation of these capacitance errors, and tuning at 352.2 MHz operating frequency, is evaluated using method described in [3]. Resulting values (without any safety margin) are shown in table 3.

Table 3: Calculated tuner position range

Tuner	min position (mm)	max position (mm)
slugs	-4.0	+30.5
RF port	0	+9.0

RF POWER COUPLING

RF input port follows the same design as in IPHI project. Coupling is tuned by adjusting the diameter of the coupling hole. RF simulations are used to estimate RF losses in RFQ cross section, end cells, vacuum ports.... The power dissipated by the tuner assembly is strongly dependent of tuner position range required for tuning. Beam loading is 210 kW at 70 mA beam current. Therefore, the total power provided to the RFQ may be estimated between 480 kW and 620 kW. HFSS and COMSOL softwares are used to estimate coupling for different hole radii (Figure 8). A radius between 6 mm and 7 mm has been defined and will be adjusted during the setting of the RFQ according to tuner position.

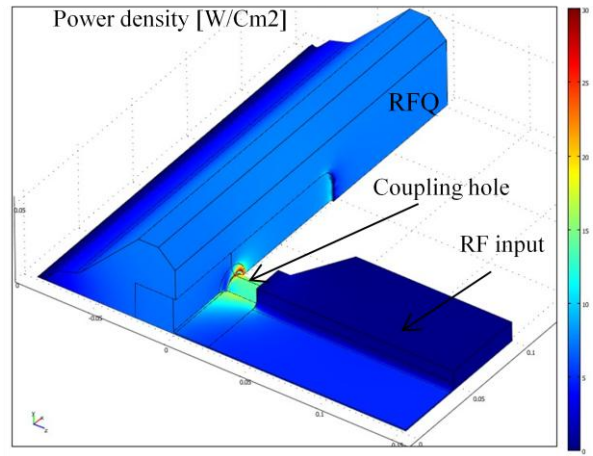


Figure 8: RF power coupling

CONCLUSION

A complete analysis of the Linac4 RFQ has been performed using RF simulating codes 3D (Comsol, Soprano and HFSS) and a RFQ 4-wire transmission line model. These tools are used to calculate different systems (as end cells or tuner) required to compensate errors due to the mechanical construction.

- [1] A. Lombardi, C. Rossi, M. Vretenar, Design of an RFQ Accelerator optimized for Linac4 and SPL, CERN-AB-2007-027-RF
- [2] O. Piquet, M. Desmons, A. France Tuning procedure of the 6 meters IPHI RFQ, PAC07
- [3] A. France, O. Delferrière, M. Desmons, O. Piquet Design of slug tuners for the SPIRAL2 RFQ, PAC07