AN UPGRADE OF IPHI RFQ

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Abstract

An upgrade of the High-Intensity Proton Injector (IPHI) at Saclay is currently under study. Among the options considered, this paper investigates the feasibility of a new Radio Frequency Quadrupole (RFQ). This RFQ will build upon operational feedback from both the IPHI and ESS RFQs and operate at the same frequency of 352.21 MHz. Unlike the existing RFQ, divided into three 2-m-long RF segments, the new design would consist of a single 6-m RF segment. It will accelerate a reduced beam current, from 100 to 55 mA, while increasing the output energy from 3 to 5 MeV. The required RF power will be reduced to maintain compatibility with the current RF power supply. Power would be injected through loop couplers similar to those used on the ESS RFQ. However, their average power capability must be significantly increased to handle the 70% duty cycle, compared to 5% for ESS. This paper describes the beam dynamics design process and presents the resulting RF design.

INTRODUCTION

The new IPHI RFQ is a 6 m-long single-segment RFQ that could replace the current one, which operated from 2016 to 2025 at CEA Saclay. It will enable acceleration of protons to a higher output energy [1, 2].

The design is strongly based on the ESS RFQ, the most recent design developed at CEA at the same frequency. However, thermomechanical constraints are more severe due to the higher duty cycle. The RF and thermomechanical designs follow the methodology developed at CEA and detailed in Ref. [3].

RF DESIGN

Beam Dynamics Specifications

The vane modulation of the RFQ has been optimised using the TOUTATIS solver. This allowed reaching a Kilpatrick limit of 1.64 Kp and an output energy of 5.036 MeV. The inter-vane voltage increases sinusoidally from 76.2 to 91.3 kV for a beam current of 55 mA at 70% duty cycle. This voltage level, lower than in the ESS RFQ, contributes to reducing RF power losses in the copper. The transmission is expected to exceed 99%. The RFQ length ensures a frequency separation around 1 MHz between the accelerating mode and the closest dipole mode. The main beam dynamics parameters are shown in Fig. 1.

Transmission Line Model (TLM)

From an RF point of view, an RFQ can be described as a waveguide circuit composed of 3D end structures connected by multiple constant-section waveguide segments. It can therefore be modeled using a transmission line model (TLM),

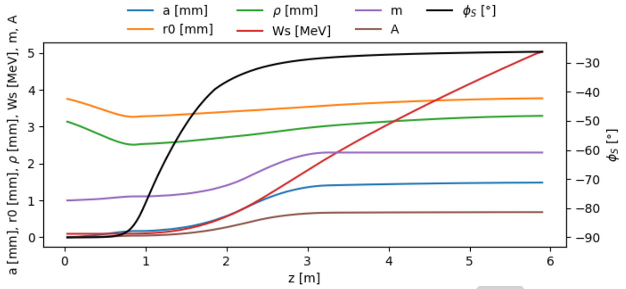

Figure 1: Beam dynamics parameters computed with TOUTATIS along the RFQ.

consisting of distributed capacitances and inductances (see Fig. 2).

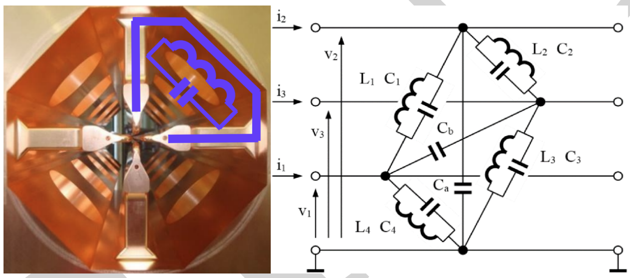

Figure 2: TLM representation. Left: electrical circuit corresponding to the geometry. Right: equivalent four-wire transmission line model.

The design is strongly inspired by the ESS RFQ, but also keep IPHIs elements. A variable-length and variable-width vane geometry has been adopted. This allows the local frequency to be tuned solely via the distance of the J_1 point on the vane with the beam axis (see Fig. 3). This results in a constant backing plate geometry, which is simpler to machine and cool. It differs from the ESS design, where he J_1 point is fixed and the cutoff frequency is adjusted through the backing plate geometry.

The vane design procedure has been improved. Traditionally, several iterations between TOUTATIS and RF solvers were required to converge towards a solution compatible with both beam dynamics and RF constraints. In particular, TOUTATIS does not account for cases where certain vane geometries would require an excessively large cutoff plate to reach the target frequency. Here, an additional constraint was introduced into TOUTATIS to ensure that the generated vane geometry leads to a reasonable cutoff plate size. The procedure is detailed in [4].

Each cell was simulated using the eigenmode solver of CST Studio Suite®. The inter-vane voltage V is then computed from the angular frequency ω and the magnetic field flux through the cross-section S of a cell of length L_{cell}:

$$V = \int_S \omega \mu_0 \vec{H} \cdot \vec{dS}. \qquad (1)$$

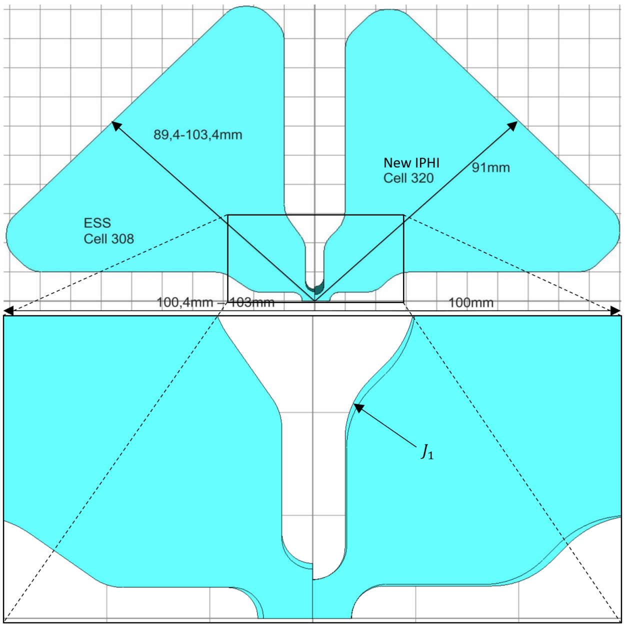

Figure 3: Geometrical comparison between ESS and new IPHI RFQs.

The per-unit-length capacitance and inductance are obtained from the stored energy W:

$$C = \frac{2W}{L_{cell}V^2}\ ,\ L = \frac{1}{\omega^2 C}. \qquad (2)$$

This yields the RFQ transmission line model, enabling theoretical studies of cavity modes and tuning behaviour. The estimated RF losses in the 2D model are 461 kW.

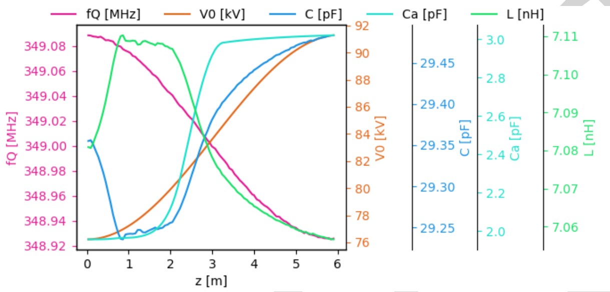

Figure 4: Local capacitance (C and C_a), inductance (L), cutoff frequency (f_Q), and inter-vane voltage (V_0) along the RFQ computed with CST.

Tuner and Vacuum Port Considerations

Fabrication error compensation is achieved using stubs spaced by 330 mm, three per section per quadrant. Their number (18) and diameter (80 mm) provide sufficient flexibility to reproduce the voltage law accurately while limiting RF losses due to penetration depth. The required local inductance variation for cavity tuning has been derived from CST simulations (see Fig. 5). The tuners are nearly identical and induce a local perturbation on the voltage law below 0.5%.

To ensure vacuum pumping without RF field leakage into the pumps, grids are directly machined into the RFQ body,

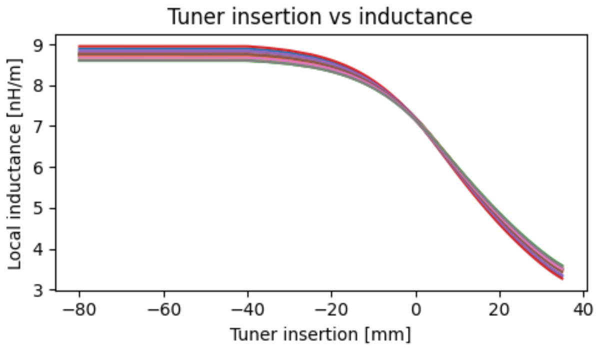

Figure 5: Local inductance variation induced by tuners.

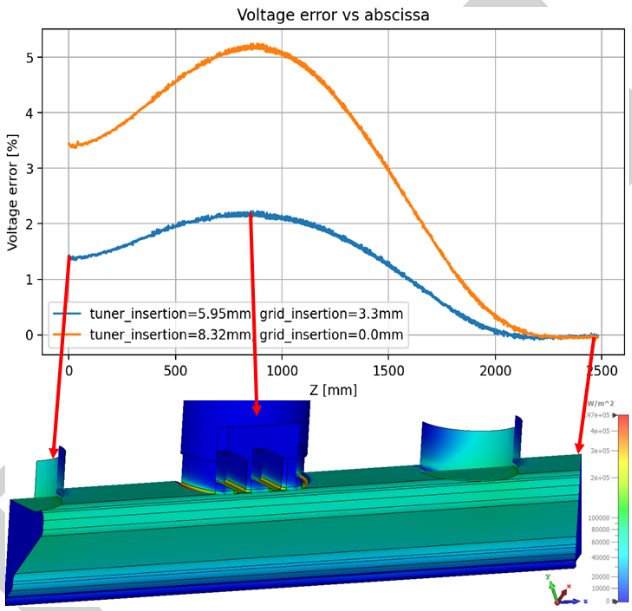

Figure 6: Top: impact of tuners and grids on the voltage law. The grid significantly increases the voltage error, particularly when it is flush. Bottom: surface power density, which is strongly enhanced in the grid regions (grid insertion: 3.3 mm).

simplifying both design and cooling. The cooling layout is relatively complex, as it requires one cooling channel per vane, as well as additional channels around the pumping grids.

To compensate for the associated volume increase, they are recessed by 3.3 mm, ensuring minimal impact on the local frequency and voltage distribution. Two grids are installed for every three tuners. As shown in Fig. 6, the flush-mounted grid has a stronger impact on the voltage law, as it introduces a larger vacuum volume in the grid region. Moreover, the detuning it induces requires deeper tuner insertion, which further modifies the voltage distribution around the grid and slightly increases RF losses by approximately 500 W per grid.

Bead-pull measurements allow the longitudinal magnetic field to be determined using the perturbation method. The measurement axis is chosen to minimise disturbances induced by the grids and tuners, while maintaining sufficient sensitivity to the magnetic field, i.e. within the backing plate region. Measure points are evenly spaced and located between grids and tuners.

Manufacturing Accuracy

The allowable tuning ranges are determined from maximum capacitance errors induced by worst-case geometrical deviations. The vane tolerances are defined by parameters t and δ as follows (explained in Fig. 7):

- the center of the vane end must lie within a square of side $2t$ centred on the nominal position,
- the vane radius error is bounded by δ.

Table 1: Tuner position limits in mm as a function of t and δ. Red entries lie outside the linearity range and may render the RFQ untunable.

t \ δ	**10 µm**	**20 µm**	**30 µm**
10 µm	[0.03 ; 11.0]	[-3.51 ; 13.6]	[-7.98 ; 16.2]
20 µm	[-3.74 ; 13.7]	[-8.30 ; 16.4]	[-15.0 ; 19.1]
30 µm	[-8.63 ; 16.6]	[-15.5 ; 19.3]	[-31.3 ; 22.2]

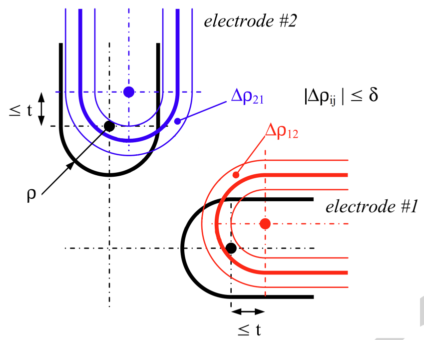

Figure 7: Geometrical definition of tolerances.

The parameters t and δ vary in the ranges 10 to 30 µm. Each pair of values (t, δ) defines a geometrical domain over which the capacitance profile leading to the worst-case tuner insertion is evaluated. A 30% safety margin is applied to each extrema, and the final result is then corrected using the tuner inductance curve. The methodology is detailed in [5]. As shown in Table 1, if the tolerances are too loose, the RFQ may become untunable due to insufficient sensitivity when the tuner is too far from the RF fields.

RF Losses

The 3D RFQ model includes all RFQ cells, the tuners used for voltage law adjustment, the vacuum pumping ports, and the end regions required to ensure proper boundary conditions. The resulting RF loss budget is summarised in Table 2.

All tuners are assumed to be inserted by 26 mm, corresponding to their maximum penetration. This provides a conservative estimate, since the final tuning configuration is not known at this stage.

Table 2: RF loss budget for the new IPHI RFQ.

Contribution	**Power [kW]**
2D design	461
Vacuum ports	13
Tuners at +26 mm (maximum insertion)	254
Wall roughness (+10%)	73
Total dissipated power for the 3D design	**800**

For comparison, the theoretical RF losses of the current IPHI RFQ are approximately 900 kW. In both cases, the beam loading is about 300 kW. As a result, the total RF power consumption is reduced by approximately 8%, despite the increase in output energy from 3 to 5 MeV. This improvement mainly results from the beam dynamics design, in which a lower inter-vane voltage with a more gradual increase along the structure was selected.

CONCLUSION

A new 6 m single-segment RFQ for the IPHI injector has been designed, accelerating a 55 mA proton beam up to 5.036 MeV at 352.21 MHz with a transmission above 99%. The RF design, based on a transmission line model, ensures consistency with beam dynamics constraints while remaining compatible with the existing RF infrastructure. Thermomechanical studies indicate that the proposed cooling scheme can sustain the required 70% duty cycle with acceptable detuning. Overall, the results demonstrate the feasibility of the upgrade within the targeted performance and operational constraints.

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