# RF DESIGN OF ESS RFQ

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*Abstract*

The low energy front end of ESS is based on a 352 MHz, 5-m long Radiofrequency Quadrupole (RFQ) cavity. It will accelerate and bunch proton beams from 75 keV to 3 MeV. The beam current is 50 mA (75 mA as an upgrade scenario) for 4% duty cycle. A complete RF analysis of the ESS RFQ has been performed using 3D RF simulating codes and a RFQ 4-wire transmission line model. Proposed RFQ is a 4-vane structure where 2D cross-section is optimized for lower power dissipation, while featuring simple geometrical shape suitable for easy machining. RF calculations are performed for the whole RFQ, and mainly for the following parts: end circuits, vacuum port, tuners and RF coupling ports. Power losses are particularly calculated in order to achieve future thermo-mechanical calculations.

## CAVITY DESIGN

The RFQ cross-section is defined in Fig. 1. Four geometrical parameters are variable vs. abscissa z along the RFQ: $r_0$, $x_{J5}$, $x_{J6}$ and $y_{J6}$. Axis to vane-tip distance $r_0(z)$ is an input parameter resulting from beam dynamics analysis; $x_{J6}(z) = y_{J6}(z)$ is designed to achieve specified voltage profile (Fig. 2) and a 346 MHz accelerating mode resonance frequency. In this way, slug tuners are dedicated to compensation of voltage errors resulting from construction tolerances only.

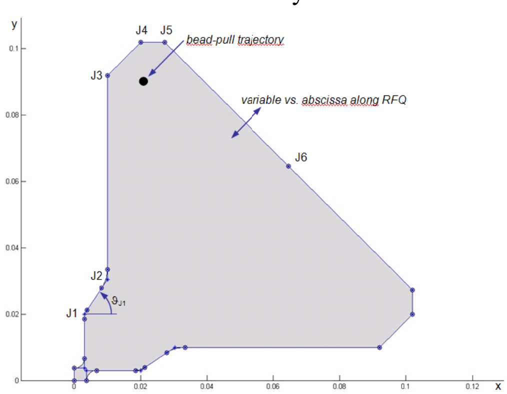


Figure 1: RFQ cross-section (x and y in meter units).

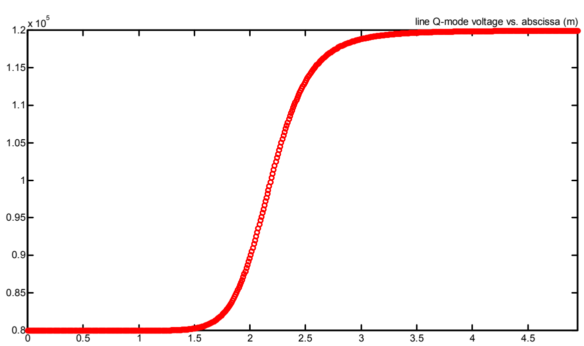


Figure 2: RFQ voltage profile (V) vs. abscissa (m).

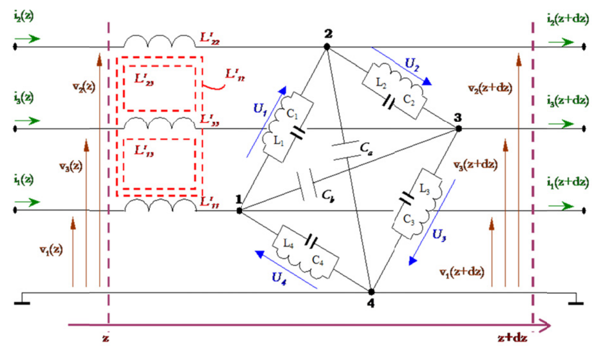

Figure 3: The 4-wire transmission line model (TLM).

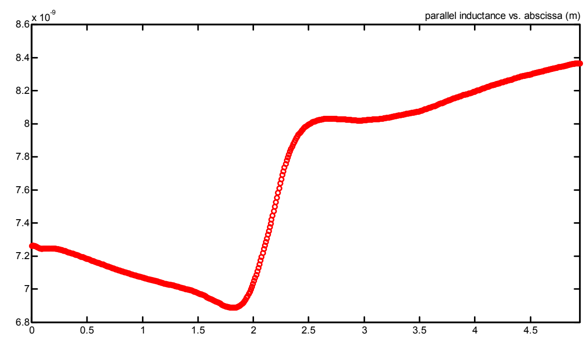


Figure 4: Parallel inductance (H.m) vs. abscissa (m) .

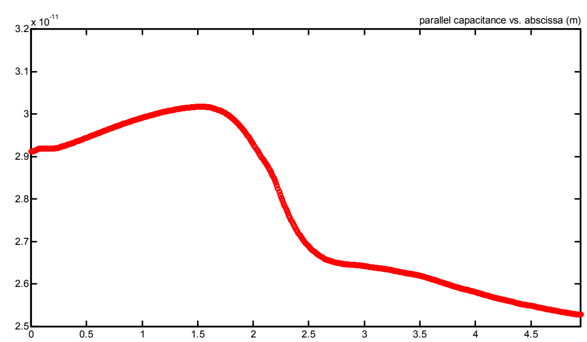


Figure 5: Parallel inductance (H.m) vs. abscissa (m) .

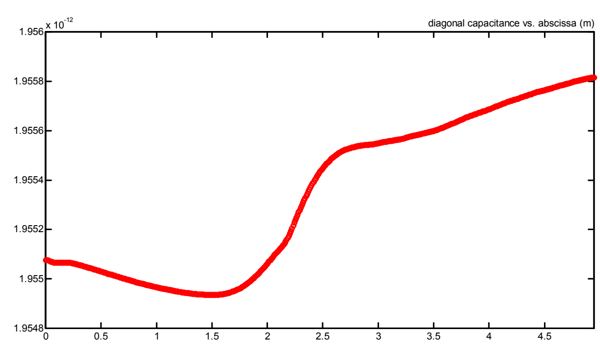


Figure 6: Parallel capacitance (F/m) vs. abscissa (m).

Resonance frequency after tuning will be 352.2 MHz. Electrical parameters needed for tuning analysis (using 4-

wire Transmission Line Model TLM, see Fig. 3) are derived from Comsol® 2D simulations, and shown in Fig. 4 (parallel inductance), Fig. 5 (parallel capacitance) and Fig. 6 (diagonal capacitance).

## STABILITY ANALYSIS

The sensitivity of RFQ to quadrupole-like and dipole-like perturbations is described by the norms of dimensionless error impulse functions $||h_{Q0,X}||$, X = Q, S or T ($Q_0$ is the accelerating mode). Each $h_{Q0,X}(z,z_0)$ function relates relative voltage perturbation $\Delta V_{Q0,X}(z)/V_{Q0,Q}(z)$ to originating "impulse" perturbation $\delta(z-z_0)\Delta C_{XQ}/C(z)$ located in $z_0$. The norms given by $||h_{Q0,X}|| = \sup_z \sup_{z0} |h_{Q0,X}(z,z_0)|$ primarily depend on frequency, RFQ length and end-circuits s-parameters defined by $dU_X(a)/dz = -s_X U_X(a)$, $dU_X(b)/dz = +s_X U_X(b)$ (z = a, b are RFQ ends abscissa). In the present case of un-segmented RFQ, $||h_{Q0,Q}||$ cannot be that much adjusted since $s_Q = 0$ is required ($||h_{Q0,Q}|| \approx 97$). A smooth optimum $32 \leq ||h_{Q0,S/T}|| \leq 80$ is found for $-2 \leq s_{S/T} \leq 0$ V/m/V. End-circuits are designed (Fig. 7) to satisfy both $s_Q$ and $s_{S/T}$ requirements with proper choices of quadrupole rods lengths (28 and 31 mm) [1] and vane undercuts (23 and 25 mm). Resulting $||h_{Q0,S/T}||$ is 39, close to optimum. Modes closer to $Q_0$ accelerating mode are $Q_1$ (+1.47 MHz), $D_2$ (−5.2 MHz) and $D_3$ (+2.6 MHz).

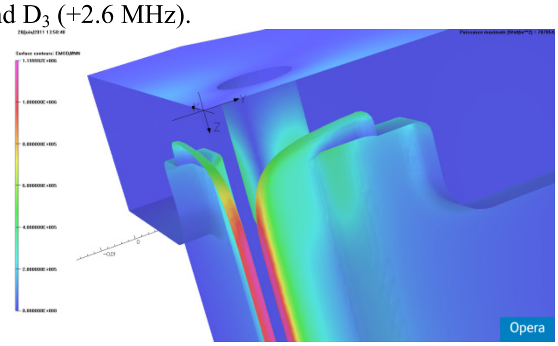


Figure 7: A view of E field amplitude at RFQ input.

## TUNING

A set of 4×15 slugs (80 mm dia., 334 mm axes spacing) will be available for tuning. Tuner 2D inductance slopes required by TLM are derived from Comsol® 3D simulations; they exhibit a linear behavior up to +30 mm position inside cavity, and are roughly independent of tuner location (Fig. 8). Tuner spacing is related to RFQ tuning process. 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). 3D simulations show that voltage accuracy is better than 1% if field samples are located at least at 82 mm from tuner axes. The resulting system of T = 15 tuner and S = 30 sampling locations is optimum in the sense that spurious spectral components of inductance eigen-functions (shown in Fig. 9) fall in rejection bandwidth of linear filter-bank used for voltage reconstruction (Fig. 10).

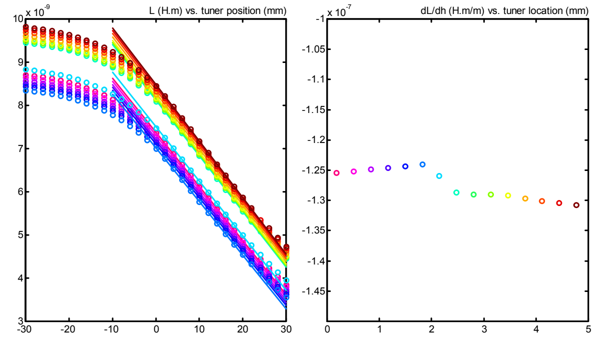


Figure 8: Left: 2D inductance vs. tuner position and tuner location (color-coded); right: inductance slope vs. tuner location (same color code).

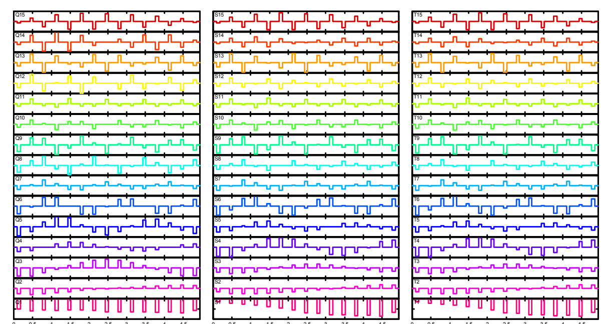

Figure 9: Inductance eigen-functions; Q, S and T subsets shown from left to right.

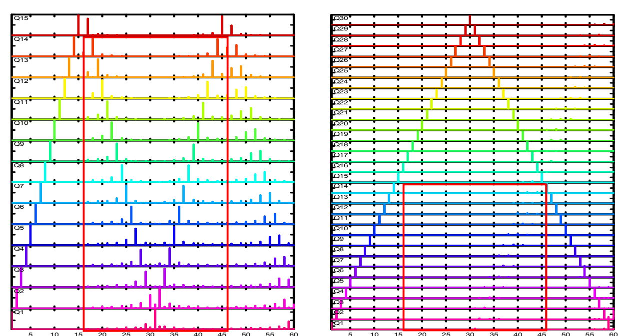

Figure 10: Left: spectral components of Q eigen-functions. Right: transmittance of reconstructing filter-bank. Spurious components in the red box are rejected.

## RF POWER COUPLING

RF power is coupled by the loop sketched out in Fig. 11; coupled power may be adjusted from 234 to 469 kW as the loop is rotated from 45° to 0° about its axis. Relative inter-vane voltage perturbation induced by the loop remains smaller than $1.8\ 10^{-3}$. The loop could be in principle located either in place of a tuner or at mid-point between two adjacent tuners. The first possibility implies that the loop would be in itself a tuner, whose position inside/outside cavity should be adjusted at each tuning iteration, with the undesired effect of varying coupling coefficient in the same time. The second possibility is then highly preferable. HFSS 3D simulations show that $V/H_z$ perturbation induced by a loop located


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between two tuners in 0 (resp. +35) mm position exceeds 1% in a 28 (resp. 48) mm interval centered about loop axis, hence a wide space is left for field samples on both sides of loop (Fig. 12).

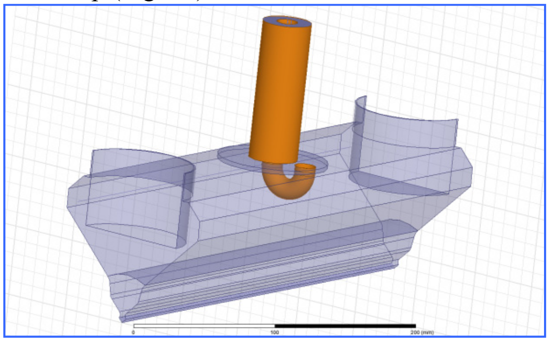

Figure 11: Coupling loop located between two tuners.

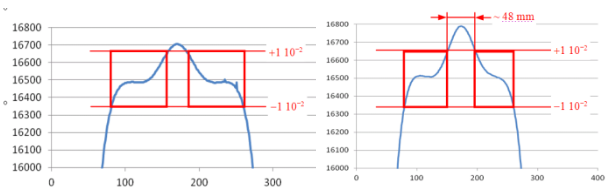


Figure 12: V/$H_z$ perturbation induced by a loop in 0° (left) and 45° (right) position, and located between two tuners in +35 mm position, is < 1% in red boxes.

## TUNER POSITION RANGE

Tuner position limits required to compensate for mechanical construction errors are derived from inter-vane capacitance errors. Tolerances on electrodes tips are defined by the two numbers t and δ:

- centre 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 ±δ.

Parameters t and δ are varied in the intervals [40,60] and [20,40] μm respectively. Each pair {t,δ} defines a capacitance relative error volume as the one shown in Fig. 13. Tuner position limits are then calculated according method described in [2], assuming constant inductance slope. A 30% safety margin is then added on either side of range, and results are corrected according to actual inductance slope. As shown in Table 1, tuner position limits approximately remain in a [−10,+30] mm interval provided that t+δ is lower than 80 μm.

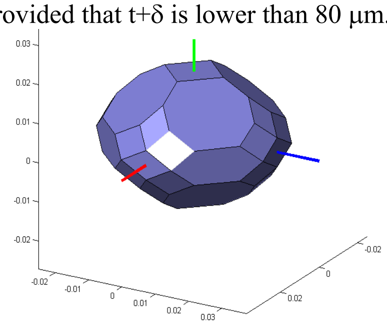

Figure 13: Capacitance relative error volume, in {QQ,SQ,TQ} axes (t = 50 μm, δ = 30 μm).

Table 1: Tuner position limits (in mm) vs. t, δ.

| | t=40 μm | t=50 μm | t=60 μm |
|---|---|---|---|
| **δ=20 μm** | +26.8 | +29.3 | +31.9 |
| | −3.1 | −6.3 | −10.4 |
| **δ=30 μm** | +29.5 | +32.1 | +34.7 |
| | −6.5 | −10.7 | −16.7 |
| **δ=40 μm** | +32.3 | +34.8 | ∅ |
| | −11.0 | −17.1 | |

## VACUUM PORTS

ESS RFQ vacuum ports are in fact identical to those of Linac4 RFQ. Accurate penetration depth is determined experimentally prior to braze [3], in order to alleviate possible numerical simulation uncertainties.

## STABILITY UNDER OPERATION

Single-mode perturbation analysis is used (prior to thermo-mechanical simulations to come) to estimate RFQ sensitivity to deformations that might occur under operation [4]: an arbitrary $10^{-4}$ capacitance relative perturbation is applied successively to all 15 modes in each Q, S and T subset. RFQ frequency shift is about 17 kHz. Voltage error reaches 1.17% for $Q_1$-like perturbation, and 0.63% for $S_3/T_3$-like perturbation. Voltage error decreases rapidly with mode index, down to 5.15 $10^{-4}$ and 6.90 $10^{-4}$ for $Q_5$ and $S_5/T_5$-like perturbations respectively. This suggests to alternate cooling water circulation from 1 m section to the next, in such a way perturbations would preferably occur on 5-th order modes.

## CONCLUSION

The un-segmented 5-meter long ESS RFQ is naturally stable with adequately designed end-circuits. Desired voltage profile is achieved with a continuously varying cross-section, in such a way slug tuners are dedicated to compensation of construction errors only. The coupling loop induces negligible voltage perturbation. Sensitivity parameters useful for cooling scheme design are given.

## REFERENCES


[1] O. Delferrière, M. Desmons and A.C. France, "A New RF Tuning Method for the End Regions of the IPHI 4-Vane RFQ", EPAC'06, Edinburgh, June 2006, POPCH105.

[2] A.C. France, O. Delferrière, M. Desmons and O. Piquet, "Design of Slug Tuners for the SPIRAL2 RFQ", PAC'07, Albuquerque, June 2007, TUPN006.

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[4] A.C. France and al., "Un-segmented vs. Segmented 4-vane RFQ: Theory and Cold Model Experiments", IPAC'10, Kyoto, May 2010, MOPD026.