

ESS RFQ: INSTALLATION AND TUNING AT LUND

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Abstract

The 352 MHz Radio Frequency Quadrupole (RFQ) for the European Spallation Source ERIC (ESS) has been delivered by the end of 2019. It has been provided by CEA, IRFU, Saclay/France. It consists of five sections with a total length of 4.6 m and accelerates the 70 mA proton beam from 75 keV up to 3.6 MeV. It will be fed with 900 kW peak power through two coaxial loop couplers. The installation process (alignment, vacuum test) as well as the tuning process based on bead-pull measurements is presented on this paper.

INTRODUCTION

Involved in the ESS Project, CEA is in charge of the RFQ design [1], manufacturing, installation and conditioning at ESS (Lund).

The RFQ, its cooling system, vacuum system and tuning system have been manufactured in 2018-2019 [2]. It has been installed and tuned in Lund by the end of 2019.

INSTALLATION

The RFQ is divided into 5 sections. Once these sections have been installed, their alignment were adjusted. A final vacuum test has been performed.

TUNING

Tuning Strategy

The tuning process follows a closed-loop algorithm [3], illustrated on Fig. 1, where “control” quantities are measured fields (acquired with the bead-pull technique), “command” quantities are tuner positions, and RFQ inverse transfer function is based on 4-wire transmission line model [4].

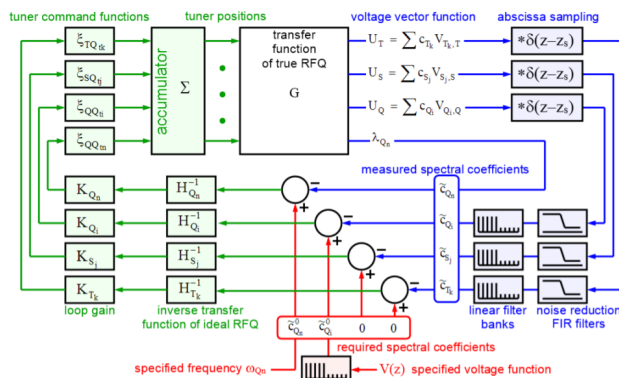


Figure 1: tuning algorithm.

The inverse transfer function however implies end-circuits parameters. Therefore, these parameters have to be tuned using rods as a preamble to the overall tuning.

Once end-circuits have been tuned and final copper rods inserted, positions of the 60 slugs are adjusted in order to achieve specified accelerating mode frequency and voltage profile. The tuning loop is iterated as many times as necessary to this purpose.

After this first tuning, couplers are inserted and their coupling is adjusted.

A final tuning is performed to compensate eventual frequency and/or voltage errors.

RFQ End Circuits

Electrical parameters of end-circuits must ensure that the desired RFQ voltage profile may be obtained at the end of the slug tuning process. End-circuits located in $z = a$ “end1” and $z = b$ “end2” are represented by 3×3 matrixes s_a and s_b (voltage logarithmic slope matrixes). Dipole sub-matrixes are expected to be symmetric and voltage logarithmic slope for the accelerator mode (Q) is assumed to be independent of the dipolar modes (S and T):

$$\begin{vmatrix} \partial U_Q \\ \partial U_S \\ \partial U_T \end{vmatrix} = - \begin{vmatrix} (s_a)_{QQ} & 0 & 0 \\ 0 & (s_a)_{SS} & (s_a)_{ST} \\ 0 & (s_a)_{ST} & (s_a)_{TT} \end{vmatrix} \begin{vmatrix} U_Q(a) \\ U_S(a) \\ U_T(a) \end{vmatrix}$$

$$\begin{vmatrix} \partial U_Q \\ \partial U_S \\ \partial U_T \end{vmatrix} = + \begin{vmatrix} (s_b)_{QQ} & 0 & 0 \\ 0 & (s_b)_{SS} & (s_b)_{ST} \\ 0 & (s_b)_{ST} & (s_b)_{TT} \end{vmatrix} \begin{vmatrix} U_Q(b) \\ U_S(b) \\ U_T(b) \end{vmatrix}$$

Adjustable quadrupole rods (aluminum) are inserted into end plates to adjust these parameters as illustrated on Fig. 2. The insertion “Lend1” and “Lend2” are calibrated using shims.



Figure 2: tunable rods on shim and inserted at one end.

For 3 different rod insertions (45 mm, 57.5 mm and 70 mm), end voltages and voltage slopes are derived from bead-pull measurements, using a set of 5 different excitations. For “end1” it has been difficult to estimate them, due to a low signal level.

Results are displayed on Fig. 3. The variation is close to linear. Resulting tuned rod length was about:

$$L_{end1} = 47.7 \text{ mm} \quad L_{end2} = 51.6 \text{ mm}.$$

Dipolar voltage logarithmic slope are estimated:

$$\langle \lambda D_a \rangle = -0.865 \text{ V/m/V} \quad \langle \lambda D_b \rangle = -0.346 \text{ V/m/V}$$

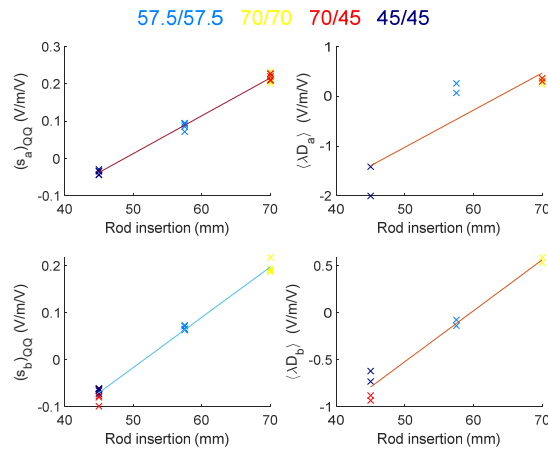


Figure 3: End boundary conditions vs. output-circuit quadrupole rod length.

Slugs and Dummy RF Blocks Pre-Tuning

The RFQ is terminated with copper end plates supporting copper tuned quadrupole rods. Slug tuners are in flush position. The 2 power couplers have been installed in the RFQ, but not coupled. This configuration defines tuning step 0. Slugs tuners are presented on Fig. 4. Their positions adjustment are illustrated on Fig. 5. Their dimensions have been set to achieve frequency and voltage profile requirements (due to the geometry errors done during the fabrication process or/and RFQ installation).



Figure 4: Slug tuners.

The maximum and minimum errors during the tuning process are displayed on Fig. 7. At the end of the 4th step, it has been found that the boundary conditions were not set

properly for the S and T modes, this explain the difficulty for the algorithm to converge properly before this step.



Figure 5: tuner position adjustment.

After 6 steps, the accuracy on the Q mode was excellent, in the interval $[-0.11\% \ 0.08\%]$ as well as the relative level of the S and T modes $[-0.90\% \ 0.69\%]$ and $[-0.25\% \ 0.25\%]$. Nevertheless, the precision of the measurements may mitigate this precision, but the overall precision should remain within the interval $\pm 1\%$.

RF Coupling

The orientation of the 2 RF power loops have been adjusted to achieve critical coupling of the beam-loaded cavity as illustrated on Fig. 6:



Figure 6: RFQ power couplers adjustment.

After this adjustment, the power required for the nominal cavity voltage without beam will be about 729 kW (713 kW for the cavity and 16 kW for the reflected power).

Final Slug Tuner Positions

The introduction of the two RF couplers changed slightly the RFQ performances. Therefore the tuning has to be finalized. The 7th step has been performed just after the coupler insertion, when the RFQ was not thermalized. No tuner position was modified regarding the 6th step. At the 8th step, the RFQ was thermalized again. New slug tuner positions were calculated and a final step (the 9th) was performed. The maximum and minimum errors during the tuning process are displayed on Fig. 7:

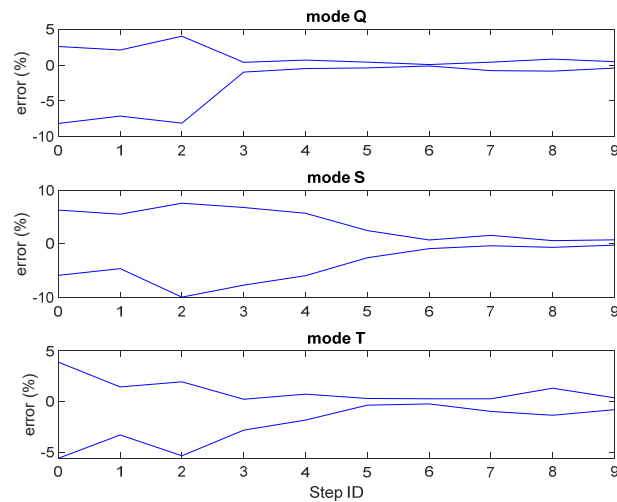


Figure 7: relative error progression during the tuning process.

The progression of the measured spectral amplitudes c_{Qi} , c_{Sj} and c_{Tk} are displayed on Fig. 8.

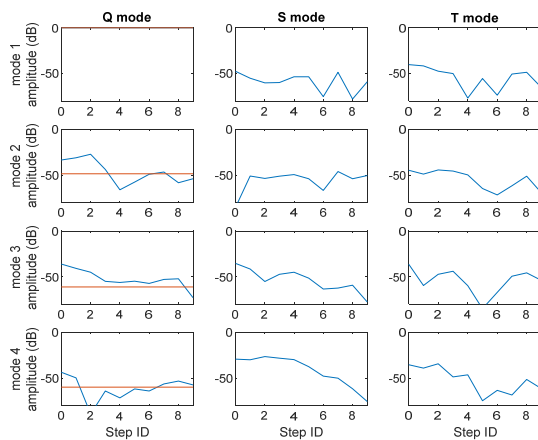


Figure 8: progression of the measured spectral amplitudes c_{Qi} , c_{Sj} and c_{Tk} . Red lines correspond to specifications.

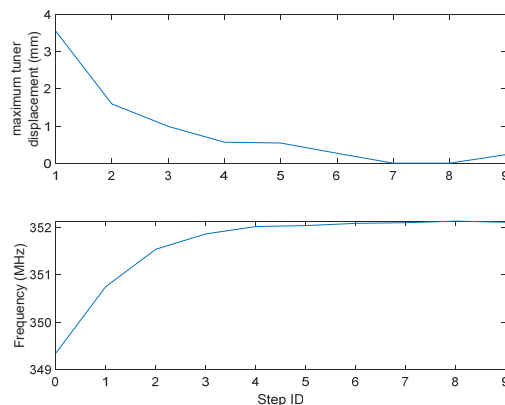


Figure 9: Progression of the tuning algorithm. Top: maximum displacement among the tuner. Bottom: Accelerator mode frequency.

The maximum displacement among the slug tuners and the Q mode frequency progression during the tuning process are presented on Fig. 9.

During the tuning process, the tuner displacements have been decreasing, while the accelerator mode voltage and its frequency were converging. At the final step the Q, S and T modes are presented on Fig. 10:

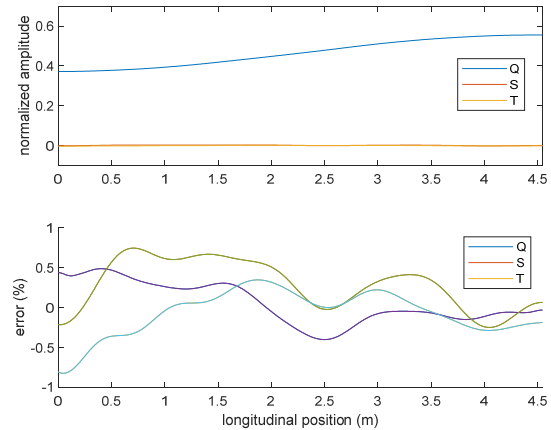


Figure 10: Q, S and T voltage vs. longitudinal position after the 9th tuning step. Top: normalized value; bottom: relative error

The accuracy for the Q mode is still very good, about $[-0.40\% +0.49\%]$ and the S and T mode voltages remain low regarding the accelerating mode, respectively $[-0.25\% +0.75\%]$ and $[-0.82\% +0.35\%]$.

CONCLUSION

The ESS RFQ was installed in Lund, its RF performances were measured. This validated the manufacturing process. Using slug tuners and quadrupole rods, the accelerating mode was finely tuned, taking into account the insertion of the two RF power loops. The final estimated relative error is lower than 1%.

REFERENCES

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