ESS-BILBAO RFQ STATIC TUNING ALGORITHM AND SIMULATION

J. L. Muñoz*, I. Bustinduy, N. Garmendia, A. Conde, J. Martin, V. Toyos, P. González,
Consorcio ESS-Bilbao, Zamudio, Spain

Abstract

The ESS-Bilbao RFQ operates at 352.2 MHz. The machining of the four RFQ segments has finished and the assembly and tuning operations will follow shortly. The static tuning and field flatness are provided by an array of 60 plunger tuners, distributed along the 3.2 meters length of the structure. There are four tuners per segment per quadrant, except for one of the segments where the ports are used by the power couplers. A bead-pull setup will provide the measurements of the field profiles, that will be collected in a matrix built up with the contributions of individual tuners. The conventional approach of inverting the matrix to get the optimum tuners distribution is explored, as well as additional optimization method. Particularly, a genetic optimization algorithm provides a very successful tuning of the RFQ. The solution provided by this approach will be used as the initial configuration of the tuners before the bead-pull measurements are carried out.

INTRODUCTION

The ESS-Bilbao RFQ [1, 2] is currently under fabrication. It will be part of the injector for the ARGITU compact accelerator-based neutron source [3]. The RFQ will accelerate protons from 45 keV to 3.0 MeV. It is a pulsed linac that operates at 352.2 MHz, and up to a duty cycle of 5 %. In order to meet the acceleration and transmission characteristics, the RFQ needs to be precisely machined and assembled. It is worth pointing out that each of the RFQ four segments, that are themselves an assembly of four components named vanes, are not brazed together. Polymeric vacuum gaskets and RF contact elements are used instead (see [1, 2] for details). The 3.12 meters long structure of the RFQ has to be tuned up so it not only resonates at the required frequency, but also has the correct field profile. This is achieved by the combined action of a set of 60 plunger tuners. The field profile along the cavity length, measured using a bead-pull technique, will be modified by the action of the tuners. The tuning of the RFQ is then the procedure of modifying the measured field profile so it becomes flat. The algorithms to do this in an optimal way, for ESS-Bilbao RFQ, are described in this paper.

RFQ TUNING

The ESS-Bilbao RFQ is designed to have a uniform intervane voltage of $V(z)$ =85 kV along all its length. In operation, the magnitude of this voltage will be determined by the RF power delivered into the cavity. The 2D cross-section of the RFQ (see Fig. 1) represents a perfect LC resonator, with a single frequency and a single value for the intervane voltage at a certain power. In the 3D cavity, the modulation of the RFQ vane tips (Fig. 2), that allows its bunching and accelerating characteristics, as well as other features of the resonant structure will modify the local capacitance per unit length, resulting in a non uniform voltage $V(z)$. Mechanical fabrication or alignment issues will also contribute to this non-uniformity.

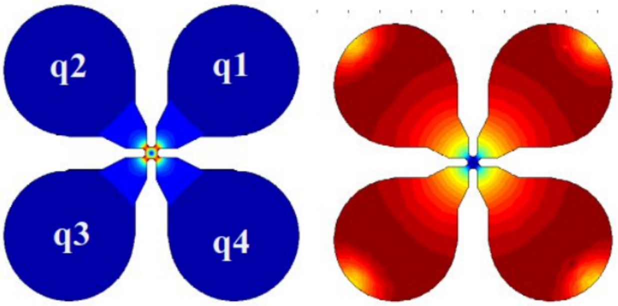

Figure 1: Electric (left) and magnetic (right) field maps for the cross section of the RFQ, with the quadrant naming specified in the electric field map.

The effect of the modulation can be calculated using a conventional perturbation approach to the transmission line model of the RFQ (see, for example, [4]). The effect of the 3D structure features, as well as the effect of geometrical deviations of the cavity, can be computed using FEM models of the RFQ. The combined effect of all deviations is a non-uniform voltage $V(z)$, that if is not corrected will affect the operation of the cavity.

These perturbations are compensated by the action of the plunger tuners. The field profiles are obtained by bead-pull measurements or are extracted from computer simulations. As described in [5], from the values along the 4 quadrants (q_1, q_2, q_3, q_4, Fig. 1), the combined magnitudes 1 are derived. From the measurements, a set of P values along z are selected. The field profile values for these selected coordinates are grouped in a vector V of size $3P$. Then, each one of the N tuners is moved a specific distance inside the cavity from the initial setup, and the curves are measured again. The perturbation caused by each tuner is assumed to be linear. In this way we can arrange the field perturbations caused by each tuner in the form of a matrix equation, Eq. (2) that includes all individual changes. This equation is the basis of all the tuning methods described here.

$$\begin{aligned} Q &= (q_1 - q_2 + q_3 - q_4)/4 \\ D_1 &= (q_1 - q_3)/2 \\ D_2 &= (q_2 - q_4)/2 \end{aligned} \tag{1}$$

$$V = MT \tag{2}$$

---

* jlmunoz@essbilbao.org

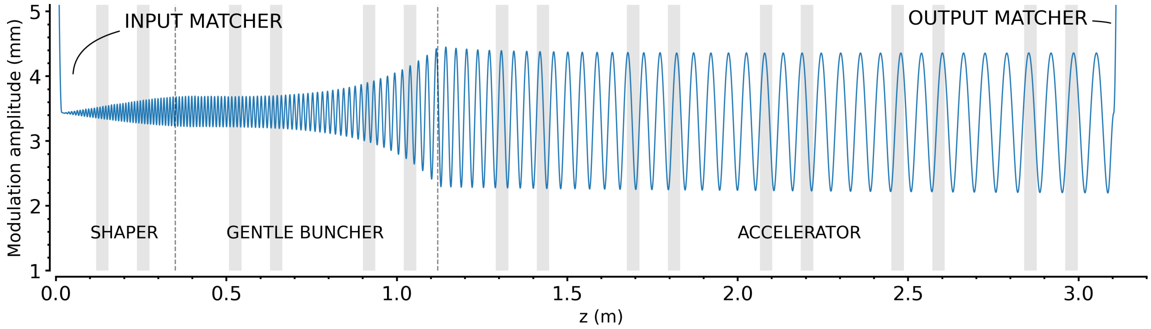

Figure 2: The ESS-Bilbao modulation curve. The shaded blocks point out the situation of the tuner ports, 4 per segment per quadrant.

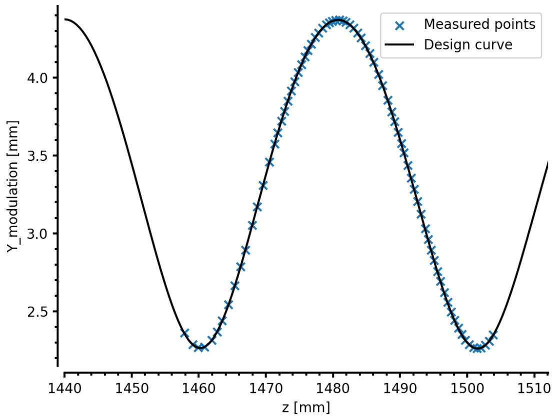

Figure 3: A measurement of the modulation of one of the vanes of the segment 2, showing the design curve and the measured data.

TUNING PROCEDURE IMPLEMENTATION

From the metrology measurements of the segments that have been already machined and assembled, it is verified that the geometric deviations in individual vanes are below 5 µm, while deviations in the assembly of the segments are below 20 µm (see Fig. 3 as an example). So, it is expected that the main deviations that the tuners will have to correct will be derived from the segment-to-segment assembly and alignment. The tuning algorithm simulations shown in this report correspond to results obtained from computer simulations of a realistic model of the RFQ. The evaluation of different tuning algorithms is done by setting the corresponding tuner configuration in the FEM simulation model and extracting the fields as in a bead-pull experiment.

Tuning Using Standard SVD Algorithm

The standard approach for tuning is to invert equation 2:

$$V = M \cdot T \rightarrow \Delta T = M^{-1} \cdot \Delta V \qquad (3)$$

In this way, we can obtain the change that is needed in the tuners configuration, ΔT, in order to obtain the desired voltage (or field) modification, ΔV. This target change will be the difference between the measured profile and the desired, constant, profile. As the matrix M is normally non square, the inverse is not properly defined. The SVD (Single Value Decomposition) algorithm (see [5]) provides a method to obtain a pseudo-inverse matrix. The method is iterative: in each step a row of the matrix is zeroed, so a solution with lower tuner displacement is obtained, although the field error will be higher.

This algorithm has been implemented and validated using bead-pull measurements of a 1-meter long aluminum model of the RFQ [2].

The initial condition the algorithm is shown in Fig. 4 as *Base*. In the figure, only the derived magnitude Q is shown for the different cases. The initial situation corresponds to a model with 60 plunger tuners in action, all penetrating the same distance into the cavity (uniform penetration), in order to reach the operational frequency of 352.2 MHz. The frequency of the cavity without tuners is 348.6 MHz, and the tuners need to penetrate about 14.3 mm in the cavity, and perturb the field profile up to a 10 % from a flat profile to increase the frequency to the correct value. The deviation from ideal behavior is more noticeable for the quadrupolar component Q, as the tuners action is symmetric for the four quadrants, resulting in a small variation of the dipolar components D_s and D_t, that are not shown in this figure.

The SVD algorithm yields the results shown in Fig. 5. For each step of the algorithm, the computed values of Q, D_s and D_t are shown, together with the maximum and minimum tuners penetration that correspond to each proposed solution. After the first step, the values of the field profile errors are close to zero, but the tuner displacements proposed (up to 15 mm) are very high for the mechanical system. The heat load will also be quite asymmetric for the cases with high penetration. A compromise solution is selected after the step number 4 in the algorithm: the tuning figures of merit are worse (still below 0.5% deviation) with tuner displacements in the range [−5 mm,5 mm]. This solution is shown in Fig. 4 as *SVD*.

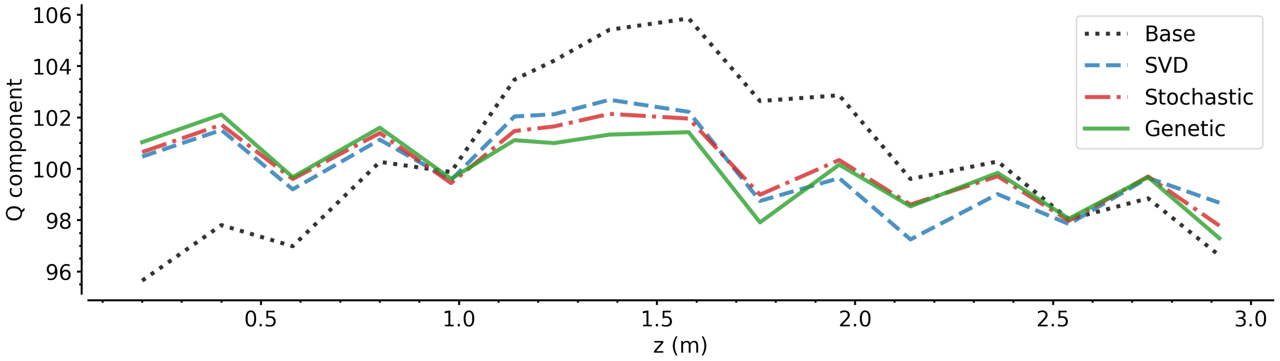

Figure 4: Profile of derived quadrupolar magnitude Q for the initial condition of the algorithm (*Base*), and for the solutions proposed by the *SVD*, *Stochastic* and *Genetic* algorithms. The stochastic and genetic solutions are similar to the SVD one, but with much lower maximum tuner penetration. Results are extracted from FEM simulations of each case.

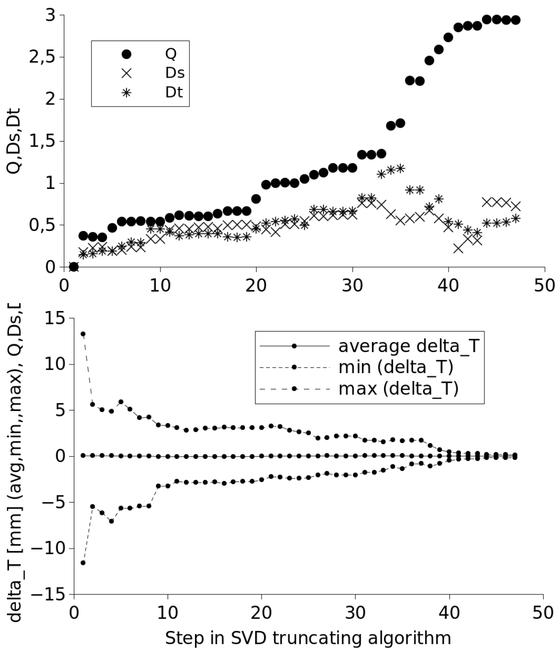

Figure 5: Results for the SVD tuning algorithm starting from the uniform situation and using 60 tuners.

Stochastic and Genetic Algorithm

An optimized tuning can be obtained by taking advantage of the linearity of Eq. (2). Two approaches are described here, a stochastic approach and a genetic algorithm, that can be used to optimize the initial tuner configurtion or to correct the deviations measured by bead-pull.

In the stochastic approach, the tuner configuration is randomly selected. Many configurations can be evaluated in very short time, and the best values are stored until a satisfactory solution is produced or the algorithm ends. A genetic algorithm has also been implemented. Selecting as optimization criteria from generation to generation the field profiles predicted by the linear model, an optimum solution can be obtained in very short time. In the case of the genetic algorithm, the tuner displacements possible values are discrete, with a separation of 0.1 mm.

In both cases, the maximum allowed tuners displacement is a chosen parameter, so all solution already fulfill this condition. Both approaches take as starting situation the one with uniform penetration, but this can be easily replaced by the profile obtained by measurements by the bead-pull system once the RFQ is fully assembled. Results for these models are included in Fig. 4. The profiles obtained for the Q profile are better for the genetic algorithm solution, that are obtained using a maximum tuner displacement of 3 mm, so the effect on the heat load and the asymmetry in the dipolar components of the fields will also be minimum.

CONCLUSIONS

The algorithms for the tuning of the ESS-Bilbao RFQ have been coded and are ready to be used when the RFQ is finally machined an assembled in 2024. The conventional SVD algorithm has been implemented, as well as two other algorithms, an stochastic and a genetic algorithm that yield optimum results.

REFERENCES

[1] J.L. Muñoz, I. Bustinduy, I. Rueda, and D. de Cos, "Development of the radio frequency quadrupole proton linac for ESS-Bilbao", *EPJ Web of Conf.*, vol. 231, p. 02001 , 2020. `doi:10.1051/epjconf/202023102001`

[2] I. Bustinduy, *et al.*,"Advances in the ESS-Bilbao injector", *J. Neutron Res.*, vol. 24, pp. 261–272, 2022. `doi:10.3233/JNR-220043`

[3] M. Perez *et al.*, "ARGITU compact accelerator neutron source: A unique infrastructure fostering R&D ecosystem in Euskadi", *Neutron News*, vol. 31, pp. 19-25, Dec. 2020. `doi:10.1080/10448632.2020.1819140`

[4] T. P. Wangler, *RF Linear Accelerators*, New York, USA, John Wiley & Sons, Ltd, 2008. `doi:10.1002/9783527623426`

[5] B. Koubek *et al.*, "RF measurements and tuning of the 750 MHz radio frequency quadrupole", *Phys. Rev. Accel. Beams*, vol. 20, p. 080102, 2017. `doi:10.1103/PhysRevAccelBeams.20.080102`