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RF TUNING ANALYSIS OF A 750 MHz CARBON RFQ FOR MEDICAL APPLICATIONS*

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Abstract

This work is part of the development study of a linac injector for hadron therapy with carbon ion beams. The initial cavities of the future injector consist of two 750 MHz Radio Frequency Quadrupoles (RFQ), which are based on the compact CERN High-Frequency RFQ. These RFQs are designed to accelerate the ions from 15 KeV/u to 5 MeV/u. Each RFQ, with a length of more of 2 meters, comprises four individual modules and 32 tuners, 8 per module.

Certain design choices, manufacturing imperfections, and misalignments lead to local variations in the frequency and field distribution within the RFQs. The tuning procedure corrects these perturbations in the TE210 operating mode using a bead pull system and movable tuners.

The aim of this article is to determine the maximum field correction achieved through this tuning without affecting the beam dynamics. For this purpose, a set of electromagnetic deviations that introduces significant dipole components to the cavity is simulated, using CST Studio. Using the tuning algorithm, this EM deviation is corrected in a realistic way.

INTRODUCTION

CIEMAT, in the framework of the IKERTU project, leads a national collaboration that includes both industrial companies and research centers. This project aims to develop an optimized linear carbon ion injector, named LINAC6+, for use in hadron therapy. Carbon ions have proven to be more precise and effective than conventional radiotherapy in treating certain types of cancer. However, the technology of the accelerators required for this therapy needs further development to optimize their performance and efficiency [1]. For this reason, the project focuses on the technological advancement of LINAC6+, which could be integrated into the initial phase of a synchrotron or a complete linac.

The study aims at enhancing efficiency and compactness while mantaining a careful beam dynamics design. The baseline linac layout involves an EBIS ion source, 750 MHz RFQ and IH-DTL cavities, capable of providing C6+ ion beams up to 10 MeV/u with currents of 190 µA and pulses of 5-10 µs at repetition rates of 200-400 Hz.

Two RFQs have been designed at CERN for this purpose [2], adapted from the compact design of the proton HF-RFQ [3], with an special trapezoidal vane modulation that enhances acceleration efficiency. Table 1 lists the main specifications of the first RFQ.

Table 1: Main Specifications of the First RFQ [4]

Parameter	**Value**
Frequency	749.48 MHz
Length L	235 cm
Intervane Voltage V_0	50 kV
Surface Power Loss P_0	244 kW
External Quality Factor Q_{ext}	5000
Coupling Strength	1.35
Number of Tuners	32
Number of Couplers	4
Number of Vacuum Ports	12

Certain manufacturing imperfections, and misalignments, both in the areas of the apertures and in the more external regions, lead to variations in the capacitance and inductance of the cavity. These changes will result in a shift in the cutoff frequency f_{co}, and consequently, in the voltage distribution as follows [4]:

$$\frac{\delta V}{V} = \pi^2 \left(\frac{L}{\lambda}\right)^2 \frac{\delta f_{co}}{f_{co}} = -\frac{\pi^2}{2} \left(\frac{L}{\lambda}\right)^2 \left(\frac{\delta C}{C} + \frac{\delta L}{L}\right) \quad (1)$$

This variation in voltage will also be reflected in the magnetic fields of each quadrant. This can be quantified by the following three components: a quadrupole component Q and two dipole components D_S and D_T, defined as:

$$Q = \frac{B_1 - B_2 + B_3 - B_4}{4}, D_S = \frac{B_1 - B_3}{2}, D_T = \frac{B_2 - B_4}{2}$$

The appropriate sign must be assigned to account for the alternating orientation of the TE210 quadrupole mode field in the four quadrants B_i. In the absence of any errors, the dipole components D_S and D_T would be zero, and the quadrupole component Q would correspond to the correct magnetic field in each quadrant.

In the case of misalignment, the tuning process involves correcting the mixing of resonant dipole fields by adjusting

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the inductance. This is done by inserting tuners at a specific depth into the cavity walls. To meet the tuning requirements of the medical HF-RFQ [5] and ensure it is acceptable for beam dynamics, the goal is to keep the dipole component $D_s = D_t$ below 2%. Additionally, to achieve a constant voltage within the cavity, the parameter δQ, which represents the variation in the cuadrupole component along the RFQ length, must also remain below 2%.

BEAD-PULL SYSTEM

A bead-pull system has been designed and installed at CIEMAT (Fig. 1) premises for field measurements and tuning of the 750 MHz RFQ cavities, and also could be ready to be adapted for other type of structures such as IH-DTLs.

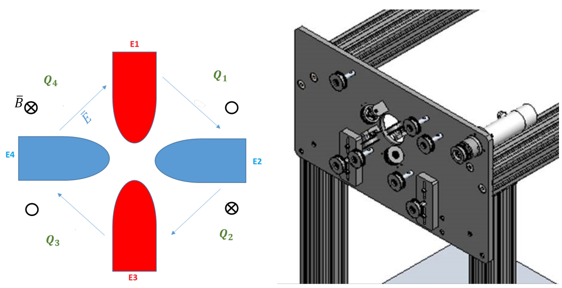

Figure 1: Cross section of RFQ vanes showing the electromagnetic fields. On the right, the pulley system designed to move the bead through the four quadrants is shown.

TUNING PROCESS

The first RFQ design is constituted by four modules, four RF power couplers, pumping ports, antennas, and 32 tuners. Each tuner is designed with an extra length, providing a mechanical tuning range of ±11 mm. With the help of a tool specifically manufactured for the tuners, they can be moved in and out within guiding cylinders, allowing for precise adjustments of 10 µm. After studying the tuner final positions, they will be remachined to the exact required length and installed in a fixed position with copper gaskets to ensure a secure seal and optimal electrical contact.

The tuning process is based on the algorithm used for tuning the HF-RFQ [5], which employs a response matrix R. This matrix details how adjustments to each tuner impact critical parameters such as frequency, Q, D_s, and D_t. The tuning is guided by solving the equation:

$$\vec{x}_{\text{trg}} = \vec{x}_{\text{cur}} + R^{\dagger}\Delta\vec{y} \quad (2)$$

where $\vec{x}_{\text{trg}}$ denotes the target tuner positions, and $\Delta\vec{y}$ represents the deviation between the current and desired values.

The matrix R is inverted using singular value decomposition (SVD), which produces multiple potential solutions. After selecting a solution in accordance with the specified requirements, the fields are measured to determine if the frequency deviations and dipolar fields are corrected. If the corrections are insufficient, the tuner positions are iteratively adjusted through multiple steps, keeping the matrix R unchanged, thus avoiding the need to repeat the sensitivity simulations.

Additionally, to treat frequency as a dimensionless variable, a specific weight is assigned. This weight modulates the influence of the measured frequency relative to the field amplitudes, which is crucial for balancing the frequency's impact within the tuning algorithm.

BEAD-PULL SIMULATION AND CORRECTION

In this work, a realistic tuning process was simulated by introducing a series of errors in the first three modules. The flatness of the quadrupolar component Q is not taken into account because the magnetic fields in each quadrant of each module, when analyzed individually, have different profiles.

The errors introduced in each module include displacements of the vanes in various directions and a modification to one face of the Q_4 quadrant in Module 2, where the magnetic field is present. These displacements were added considering the sensitivity range of fields and frequency studied in [6]. Table 2 shows the errors D_s, D_t and frequency shift in each module as a result of the simulated displacements. The simulations were carried out using CST Studio software [7].

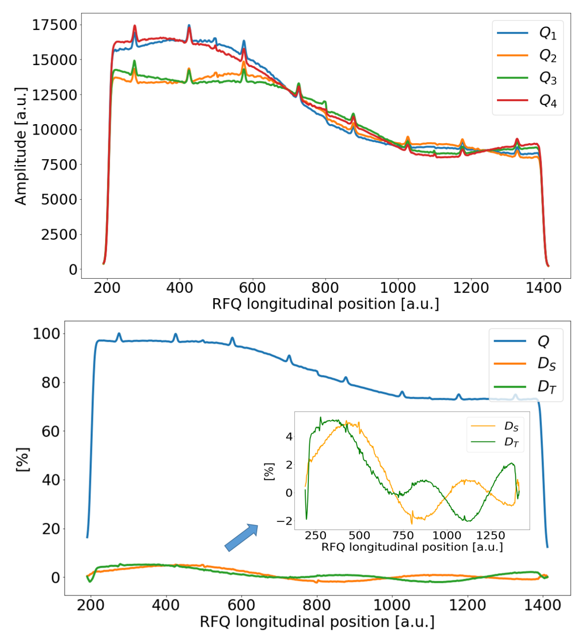

Figure 2: The magnetic fields of each quadrant (top) and the quadrupole and dipole components (bottom) for the 1-RFQ with errors.

Considering the mentioned errors and with the tuners in their nominal positions, it is observed that the RFQ fields show a dipolar error of up to 5% for D_s and D_t, as well as a difference in the quadrupolar component δQ of 20% from one end of the RFQ to the other (Fig. 2). The measured frequency is 751.52 MHz, which is 2 MHz higher than the target frequency.

These electromagnetic deviations result in a 5% increase in emittance within the beam dynamics compared to the

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Table 2: Simulated dipolar errors and the frequency shift were compared with the original RFQ design without errors for each module.

Module	**Displacement**	D_S	D_T	δ **Freq**
1	Displacements of 3 vanes ranging from 10 to 30 µm	4.9%	6.8 %	497 kHz
2	Displacements of 1 vane by 10 µm + 75 µm drop in the Q4 face	6.0%	3.9%	-26 kHz
3	Displacements of 4 vanes by 10 µm	5.3%	9.1%	3.7 MHz

nominal values, as well as a doubling of the beam size to approximately 0.4 mm [8].

To solve Eq. (2), the matrix R is obtained by displacing each tuner by 3 mm while the others remain in their nominal positions. At the same time, the frequency difference caused by these displacements is measured (Fig. 3).

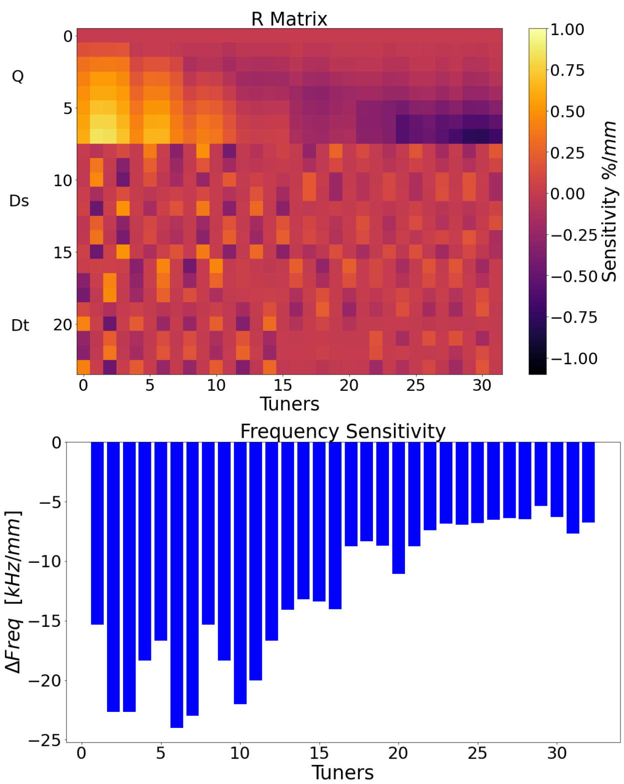

Figure 3: Response matrix for Q, D_s, and D_t at the 8 intervals of longitudinal points of RFQ (top) and frequency sensitivity for each tuner (bottom).

Figure 4 shows the steps taken to reduce dipolar, quadrupolar, and frequency errors, along with their values for each longitudinal point interval studied. Due to the significant initial dipolar error, the frequency weight was reduced to $1 \times 10^5\ \mathrm{Hz}^{-1}$ to increase the correction of the fields.

With a total of three steps Fig. 4, the Q field is uniformized from 25% to 2%. The dipolar components also remain below 2%, although with the exception of Ds at one of the measurement locations upstream of the RFQ. Although the algorithm reduces the resonance frequency, it does not manage to adjust it properly to the nominal value, requiring a final adjustment of all the tuners with a proportional displacement.

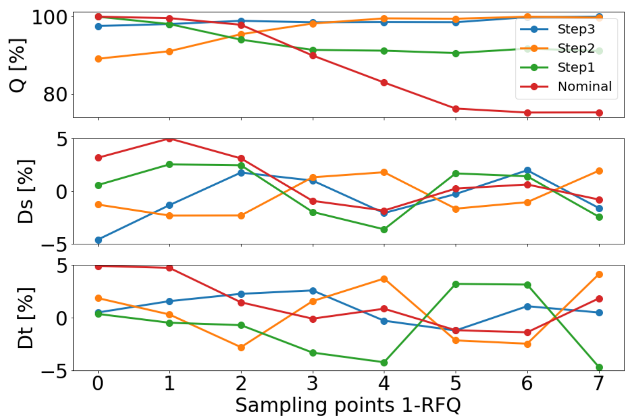

Figure 4: First three steps performed on RFQ1 using the tuning algorithm. The simulated frequency in the last step is equal to 747.5 MHz.

Thanks to the final frequency adjustment, 749.52 MHz was achieved, with the dipole components slightly larger by about 2%.

SUMMARY AND CONCLUSIONS

This study aims to simulate realistic conditions of significant errors that might be encountered in the first prototype of a Carbon ion RFQ, which will be manufactured and commissioned in the bead-pull measurement system at CIEMAT. The CST simulation facilitates the evaluation of an algorithm previously developed [5], which has demonstrated effectiveness in adequately suppressing unwanted dipolar components during RFQ operation.

The analysis indicates that when tuner displacements are significantly large, leading to substantial dipolar and Q errors, the linearity of the response matrix R may be compromised after several iterations. Consequently, it is recommended to repeat the measurement of the matrix R if the errors exceed certain thresholds to ensure accurate correction and maintain the effectiveness of the RFQ tuning.

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