TUNING THE IFMIF 5 MEV RFQ ACCELERATOR

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Abstract

In order to allow proper operation of the IFMIF RFQ, it is necessary to perform a campaign of RF measurements on the cavity aimed, on one hand, at determining the basic RF parameters (frequency, Q_0, etc.), on the other hand at verifying the fulfilment of the voltage law within the specified admitted range (±2% target value, ±4% acceptance value) of any of the perturbative components upon successive tuner settings as predicted by the tuner algorithm. These measurements also involve the determination of the proper depth of the end plates and the positioning and length of the Dipole Stabilizers (if any). In this contribution the tuning procedure and the results of such measurements will be presented for the case of the IFMIF RFQ will be described.

INTRODUCTION

The tuning of the whole 9.9 m, 175 MHz IFMIF RFQ [1] was completed at the IFMIF-BA Rokkasho site (Japan) and all the 108 slug tuners were machined to length and installed. The diameter of each tuner and RF port is equal to 90 mm and the diameter of each tuner is equal to 89 mm. The tuner depths inside the RFQ volume were determined by iterative application of the tuning algorithm [2]. The RF measurements were performed with the bead pulling perturbation technique, by making use of aluminum ogive-shaped beads 16 mm diameter and 60 mm length placed on each quadrant bisector at 170 mm height from the beam axis, 50 mm clear from RFQ upper walls. In this way it is possible to measure the quantity

$$v_{sl}=\sqrt{\left(\frac{\mu_0}{2}\right)|\mathbf{H}|^2-\varepsilon_0\ |\mathbf{E}|^2}$$

Then the vane voltages in each quadrant $V_1(z)$, $V_2(z)$, $V_3(z)$ and $V_4(z)$ are inferred from this quantity by comparison to SUPERFISH calculations. Finally, the three modal components $V_q=(V_1+V_2+V_3+V_4)/2$, $\delta V_{qd1}=(1/\sqrt{2})*(V_1-V_3)$ and $\delta V_{qd2}=(1/\sqrt{2})(V_2-V_4)$ can be determined. The beads are moved along the RFQ with the usage of a set of four motors in dc that are computer controlled with LABVIEW. Such motors move through a system of pulleys four dielectric threads of 0.8 mm diameter. All the bead-pull measurements were performed with an Agilent E5071C Vector Network Analyzer by measuring the phase shift of the S_{21} parameters at the resonant frequency.

Before assembly of the whole RFQ [3], all the 18 mechanical modules (550 mm each) were separately RF and mechanically tested along their production phases [4]. It is worth noticing that the RFQ consists of 1 e.m. segment, therefore no coupling cells are foreseen.

TUNING STEPS

In the initial setup the RFQ was equipped with dummy aluminum tuners and with dummy end plates. Each end plate can be inserted in the RFQ volume in the range 0-25 mm (with the exception of 180 mm diameter around beam axis), in order to allow boundary condition tuning as well.
Measurement Step 0 consisted of the determination of mode Spectra and field profile with tuner flush and dummy end plates at nominal insertion of $h_{EC1}=h_{EC2}=12$ mm on both sides of the RFQ. The TE_{210} Quadrupole mode frequency fq_0 was equal to 174.250 MHz. This result has to be compared with the theoretical value of 174 MHz and is in good agreement with the estimation of 174.33 MHz obtained by considering the outcomes of the RF and mechanical measurements of all the 18 modules [3]. Moreover, the dipole-free region is quasi-symmetric, since the frequencies of the neighbouring D modes fd_2 and fd_3 are equal to fq_0-1.9 MHz and fq_0+1.5 MHz respectively. The results of this measurement are shown in Fig. 1.

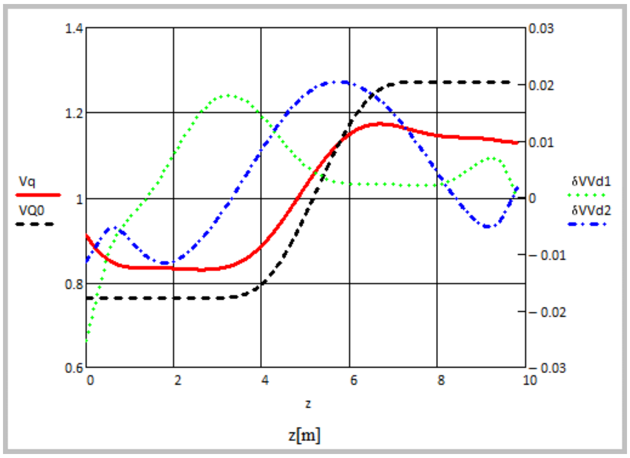

Figure 1: The modal voltage component (A.U.) vs z[m] measured with flush tuners and end plates at nominal settings. Vq and Vq0 are the measured and the nominal voltage, respectively. The components are normalized to 1. The dipole components are in the secondary scale for ease of reading.

From this measurement it is possible to notice that the quadrupole perturbation $\delta V_q=V_q-V_{q0}$ is within ±0.2 V_{q0} and that dipole perturbations are already within the specs; this is a confirmation of the dipole-free region symmetry. Therefore the installation of dipole stabilizing rods was skipped and none of such devices was put in place.
In the following Step 1 the depths of the end plates were changed in order to get the proper boundary conditions and to make the curve Vq(z) get closer to Vq0(z). In this phase

the tuning algorithm was preliminary applied (no frequency correction implemented). The final settings for the end plate insertion are equal to h_{EC1}=20 mm (Low Energy Side) and h_{EC2}= 12 mm (High Energy Side). In this situation $|\delta V_q| \leq 0.05\ V_{q0}$.

In Step 3, the aluminum tuners were moved according to the tuning algorithm, in order to reduce the amount of perturbative components. In Fig.2 the positions of the tuners along the RFQ is shown. It has to be noticed that there are 92 active tuners (23/quadrant), available for tuning (44 of them are pick-up equipped for field profile monitoring during high power operation). The remaining tuners are flush, since they act as plugs. The tuners are less dense in the first RFQ modules, due to the presence of vacuum ports and inserts. In all these measurements, the coupler ports are replaced by aluminum flush plugs. The tuner sensitivity is equal to about 1 kHz/mm per tuner.

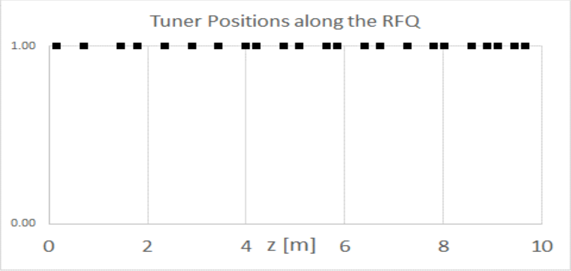

Figure 2: Tuner positions along the RFQ.

The presence of the tuners (and also vacuum ports), induces large bumps on the measured data and, for this reason, not all the measured points are useful for measurements. Therefore, a series of 42 points to be interpolated was chosen out of the 1601 measured ones. In Fig.3, the comparison between the raw phase data (dotted curve) and the interpolated data (9th order polynomial) is shown. The points of interpolation are also indicated (solid circles).

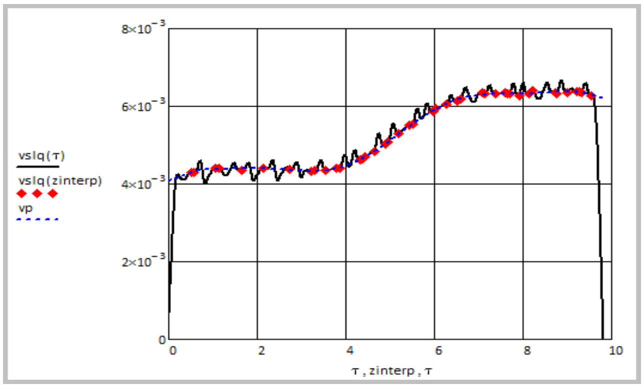

Figure 3: $v_{sl}(z)$ vs z[m] (Q component, A.U.): black curve: raw data, red: interpolated points, blue curve: interpolated data.

After a few tuning iterations, the target specifications were met ($|\delta V_q|/V_{q0}$ ≤ 0.015, $|\delta V_{qd1}|/V_{q0} \leq 0.015$, $|\delta V_{qd2}|/V_{q0} \leq 0.015$).

In Step 4, the effect of the couplers was investigated: in order to perform this check, a dummy aluminum coupler was inserted. Since in the RFQ there are 8 couplers and that P_{beam} is approximately equal to the power dissipated in the Copper P_{Cu}, the optimum β_0 for each coupler is equal to about 0.25. Therefore, this coupler was rotated in order to have β_0 =0.25 and the effect on frequency was checked. Since the loop induced detuning was equal to about -1 kHz, it is possible to assess that the effect of a coupler is equivalent to the effect of 1mm extraction of a plug located in the same coupler port. Therefore, in each coupler port, all the plugs were extracted of 1 mm. The subsequent RF measurement did not show any change in the voltage shape more than ±0.3 %, in accordance with HFSS simulations on a simplified constant-section RFQ. Then, it was proceeded to the installation of copper slug tuners. This operation was done in three batches, as it will explained in the following. It has to be noticed that, since copper the tuners have a 2 mm chamfer each at their lower base, while the aluminum tuners have a sharp edge only, this effect was taken into account while setting copper tuner insertion depth.

In Step 5, the first batch of 16 copper tuners replaced the aluminum ones. In order to have margin for correction at the end sections of the RFQ, it was decided to involve, in this batch, only the central RFQ modules.

In Step 6, the dummy end plates were replaced with the definitive copper ones at both RFQ ends. On the geometric point of view, the latter have 2 mm rounded edges, while the former have sharp edges. The related measurements showed a slight increase of Q component voltage slope at the LE end, while the D1 and D2 components were anyway within target value. This fact was interpreted as an increase of the end plate frequency [5]. Therefore, the tuner insertion in all quadrants in the location nearest to the end plate was reduced of 1mm. This action proved successful, since the corresponding measurement showed the disappearance of such slope (Fig. 4).

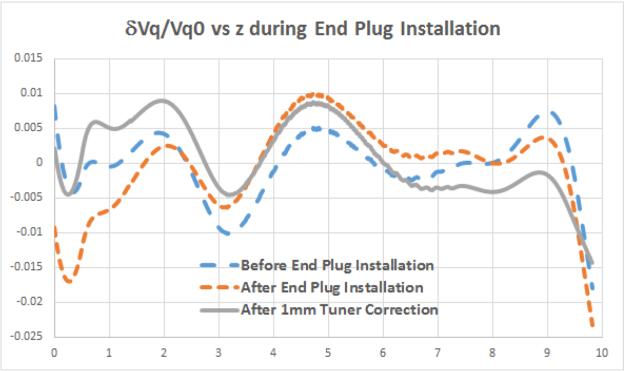

Figure 4: $\delta V_q/V_{q0}$ in the various phases of the End Plug installation vs z[m].

In Step 7, the second batch of 43 tuners was installed on the RFQ, and in Step 8 the third and last batch of 49 tuners was installed on the RFQ as well. The following Figs. 5, 6 and 7 show the final behavior of the voltage components

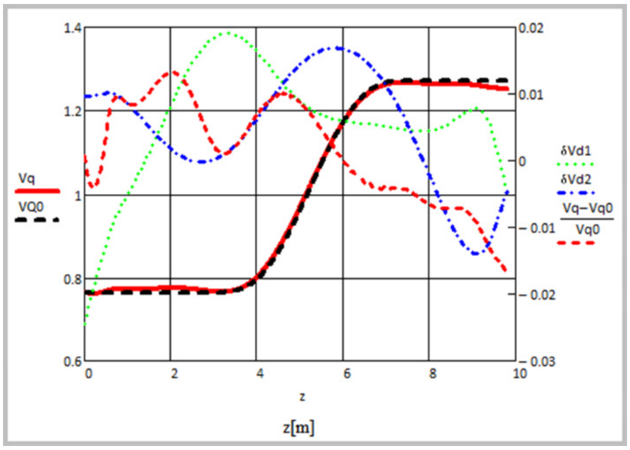

Figure 5: The modal voltage component (A.U.) vs z[m] measured after all 108 tuner installation. Vq and VQ0 are the measured and the nominal voltage, respectively. The components are normalized to 1. The dipole components are in the secondary scale for ease of reading.

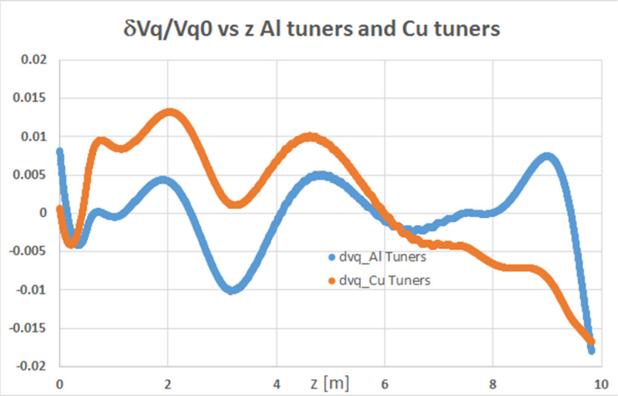

Figure 6: $\delta V_q/V_{q0}$ vs z with Al tuners (blue curve) and with Cu tuners (red curve).

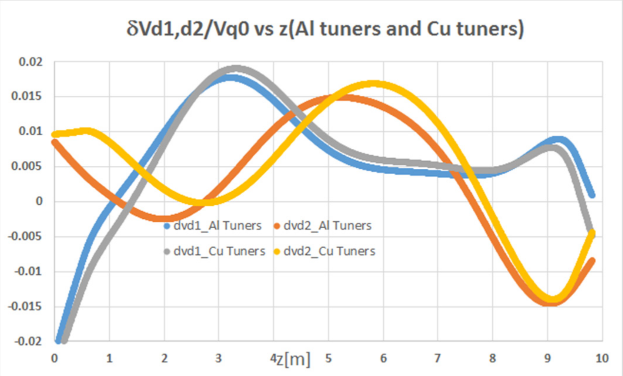

Figure 7: $\delta V_{qd1}/V_{q0}$ vs z with Al tuners (blue curve) and with Cu tuners (grey curve), $\delta V_{qd2}/V_{q0}$ vs z with Al tuners (red curve) and with Cu tuners (yellow curve).

and the evolution of the perturbative components before and after tuner installation.

Finally, in Fig. 8 the final tuner insertion depths are shown. They are well within the [-10 mm, 30 mm] range, foreseen for tuner machining.

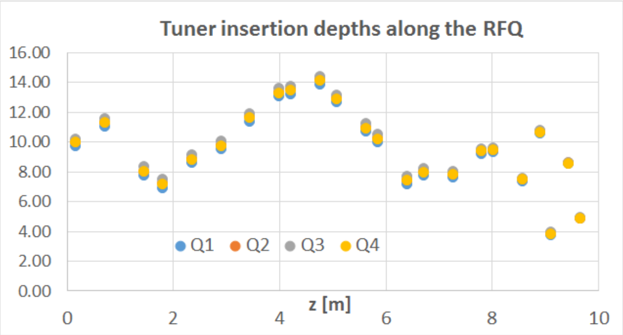

Figure 8: Tuner insertion depths vs tuner positions.

FREQUENCY AND Q$_0$ CONSIDERATIONS

The IFMIF RFQ has to work at the frequency of 175 MHz with beam on at the external temperature of 20°C and with external Atmospheric pressure. Therefore, the frequency needs to be proper rescaled at the measurement actual conditions. By taking into account: a) beam load effect on frequency is estimated of -8kHz for a 130 mA D+, b) the vacuum shrinkage and the effect of the variation of ε_r between air and vacuum c) the measured frequency coefficient of -2.9 kHz/°C, in agreement with simulations. This gives a reference target frequency in air at 20°C of 174.997 MHz. Since the final measurement was performed with Copper [Aluminum] tuners at 28.5°C [22.6°C] and the frequency was 174.989 MHz [174.994 MHz], rescaling gives a final frequency with copper [aluminum] tuners of 175.015 MHz [175.001 MHz], that is correctable with about -1°C variation of inlet water temperature channel on RFQ vessel [2].

As for Q$_0$ measurements, it was performed in three different conditions: with a dummy coupler and a field pickup, with the two measuring loops used for bead pulling, and with the same lops but in conditions of poor coupling (about 90° rotation). The average of these measurements gives a value of $Q_0=13200\pm200$.

ACKNOWLEDGMENTS

The authors wish to thank all the engineers and technicians who were involved in the design, the installation and proper operation of measurement setup as well as tuner production mounting, in particular Andrea Baldo, Paolo Bottin, Enrico Fagotti, Luigi Ferrari (LNL), Fabio Borotto and Riccardo Panero (INFN-Turin), and Ryo Ichimiya, Keitaro Kondo, Sunao Maebara and Takahiro Shinya (QST-Rokkasho), for their support.

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