# LOW POWER RF CHARACTERIZATION OF ESS BILBAO RFQ COLD MODEL

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*Abstract*

In order to test both the design and manufacturing procedures of the final ESS-Bilbao RFQ, a 1 meter long RFQ Cold Model, including a longitudinal vane modulation, has been manufactured in aluminium. Low power RF measurements have been performed to obtain the main figures of merit of the cavity, including: frequency spectrum, coupling and quality factors, tuning range, RF sealing effect and the accelerating field profile. The experimental and simulated results are explained and analyzed.

## RFQ-CM AND TEST SET-UP

In the framework of the ESS-Bilbao project, a 4-vane Radio Frequency Quadrupole (RFQ) cavity operating at 352.2 MHz is under design [1]. As a first step, in order to validate both the design and the manufacturing procedures employed, a 1 meter long RFQ Cold Model (CM) has been designed and manufactured in aluminium, as shown in Figure 1. The model includes a representative longitudinal vane modulation and a set of slug tuners symmetrically distributed. The goal is to develop an accelerating field tuning system to obtain the required field flatness along the RFQ-CM. Moreover, eight RF ports to be used either by couplers and/or pick-ups have been incorporated. Finally, extra end-walls including dipole stabilizer rods have also been designed and manufactured to investigate their effect on the resonant modes of the RFQ-CM.

Figure 1 shows the implemented test-bench to perform the measurements. It includes a network analyzer to measure the S-parameters, and an automatic bead-pull system designed in-house to sample the field in the cavity.

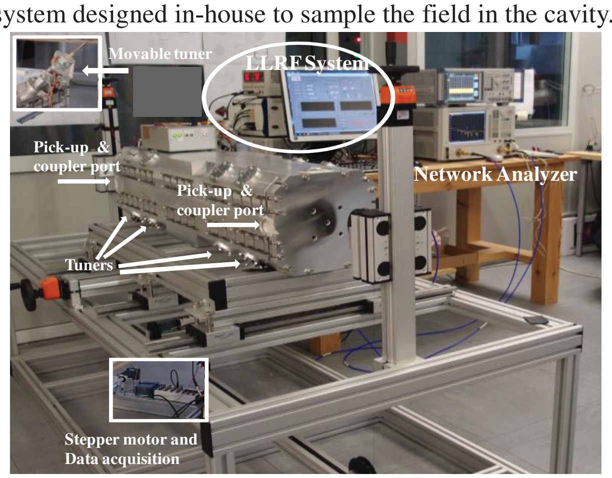



Figure 1: RFQ-CM measurement test-bench.

In the next sections, the RFQ-CM low power measurements results are presented and compared to those obtained using the commercial simulator COMSOL.

## FREQUENCY SPRECTRUM

The cavity spectral response have been measured by means of two pick-ups in transmission mode in order to minimize the magnetic loop effect in the frequency response. Table 1 shows the results obtained for the operating quadrupole ($TE_{210}$) mode, as well as the two nearest dipole modes ($TE_{110}$). All tuners are flush with the inner cavity wall.

Table 1: RFQ-CM Frequency Spectrum

| Mode | Simulated | Measured |
|---|---|---|
| Quadrupole $TE_{210}$ (MHz) | 355.1 | 356.1 |
| Dipole $TE_{110}$ (MHz) | 348.6/348.8 | 348.7/351.1 |

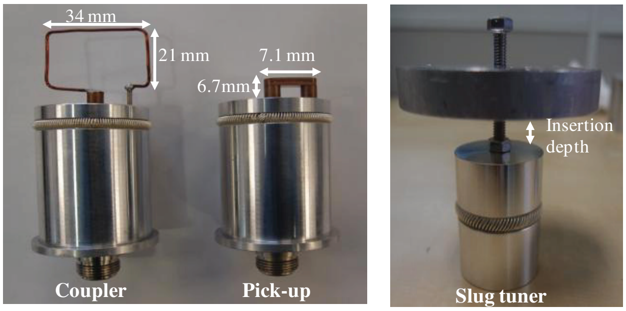
First, the obtained results show that the RFQ-CM operating mode resonates at a frequency 1 MHz above the simulated value. This is mainly due to mechanical issues. Second, one of the measured dipole modes agrees well with the ones obtained in the simulations. However, in the measurements, a significant dipole/dipole mode splitting can be observed. This is clearly due to misalignment issues, as it will be analyzed in the last section of this work.

It is important to point out that while the operating frequency of final RFQ will be 352.2 MHz, the RFQ-CM quadrupole mode was designed to resonate at 355.1 MHz. This is not an important issue, since the goals of the mock-up are fully covered in any case.

## COUPLER AND PICK-UP

The RF power will be transferred to the final RFQ by means of a coaxial magnetic coupler [2]. The loop is designed to minimize the reflected power in operation. To this end, a suitable value for the coupling factor must be chosen which depends on several parameters such us the effective loop area (depending on RFQ position and loop angle), the quality factor, the dual coupler configuration and the beam effect.

For the RFQ-CM, the coupler shown in Figure 2-(a) has been designed and the measured coupling factors agree well with the simulated ones for different positions and configurations of the couplers.




(a) (b)

Figure 2: (a) Coupler and pick-up; (b) slug tuner.

Finally, in order to perform measurements of the RFQ-CM in transmission mode, a pick-up (Figure 2-(a)) has been implemented. The pick-up coupling factor is in the range of [0.02-0.06] to cause a negligible perturbation in the cavity while sampling with enough accuracy.

## QUALITY FACTOR AND RF SEALS

The unloaded quality factor (Qo), which measures the cavity efficiency, depends not only on the cavity geometry and material but also on the surface roughness and the electrical contact between the mechanical parts.

An automated procedure to measure Qo by different methods has been developed. In our experience, the curve fitting method [3] shows a much better accuracy and repeatability than the "three point" methods.

Table 2 shows the Qo simulated value considering both ideal aluminium and aluminium with a roughness of Ra= 1.2 µm, comparable to the roughness of the manufactured RFQ-CM. As it can be seen, the measured Qo without RF seals is a 60% lower than the simulated one, which agrees with other experiences available in the literature, for instance [4],[5].

A special effort has been made in order to study the electrical contacts in the RFQ-CM by means of different types of RF seals [6]. Firstly, as shown in Figure 3, silver plated Beryllium Copper (BeCu) spring rings are used for the circular joints of the tuners and the RF ports. Secondly, BeCu finger strips are used at the end-walls flat joints and at the dipole-rods circular joints. On the other hand, the vanes are assembled by bolts without including any type of RF seal. Table 2 shows that the Qo improvement due to the RF seals in the RFQ-CM is a scanty 2.5%. The RF seal effect will be more noticeable with high power tests, where the RF leakage is avoided.

Table 2: RFQ-CM Quality Factor Data

| Simulation/Test | Conditions | Qo |
|---|---|---|
| Qo simulated | Ideal Aluminium | 8830 |
| Qo simulated | Al with $R_a$=1.2 µm | 7890 |
| Qo measured | No RF seal | 4700 |
| Qo measured | RF seal (all ports, end walls) | 4820 |

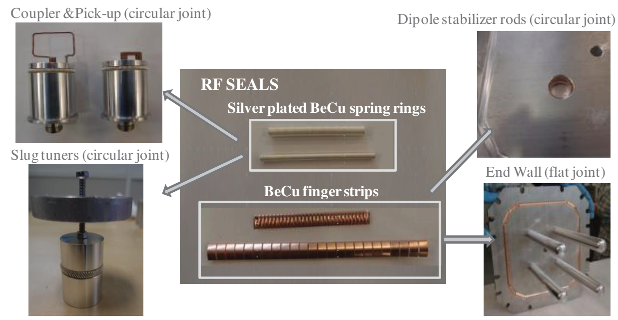



Figure 3: RF seals tested including dipole rods.

Finally, it is important to remark that Qo is also degraded by both tuners and dipole rods, since the cavity dissipation surface increases. When the sixteen tuners and dipole stabilizer rods are inside the RFQ-CM a Qo degradation up to 9% has been found.

## TUNING SYSTEM

The tuning system for the final RFQ is still under design. In any case, it should serve to both tune the operating frequency of the cavity due to mechanical errors [7] and to compensate the frequency shifts due to temperature variations. Moreover, it is necessary to obtain the required field flatness along the RFQ.

In order to validate the simulated tuning range and at a later stage, to develop a tuning algorithm to fulfill the field flatness condition, the RFQ-CM tuning system is based on symmetrically distributed sixteen slug tuners, with a diameter of 34.1 mm and a maximum insertion depth of 16 mm (Figure 2-(b)).

Figure 4 shows that the measured frequency tuning slope is 13.8 kHz/mm per tuner compared to the 16.5 kHz/mm obtained in simulations. The difference in the result is mainly again due to the fact that the measured Qo is meaningfully lower than the simulated one, as stated in the previous section.

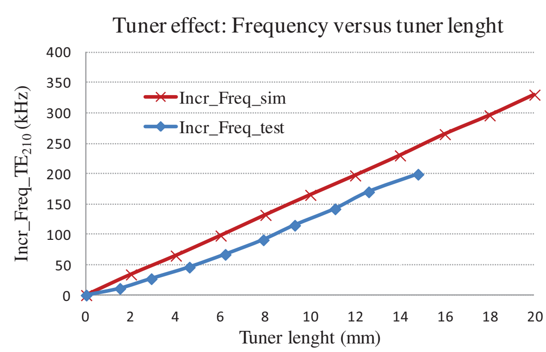



Figure 4: Frequency tuning range per tuner.

## DIPOLE STABILIZER RODS

The final RFQ could need dipole stabilizer rods with the aim of maximizing the separation between the quadrupole and adjacent dipole modes to ensure a proper operation. To this end, two end-walls with four aluminium rods each have been designed, featuring variable insertion length up to 164 mm and 20 mm of diameter (Figure 3).




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Figure 5 depicts the frequency separation between the quadrupole and the nearest neighbouring dipole mode for different rod lengths. The measured data shows a good agreement with the simulated one. Moreover, it can be noticed that the dipole rods present a negligible effect for length shorter than 60 mm, for this specific case.

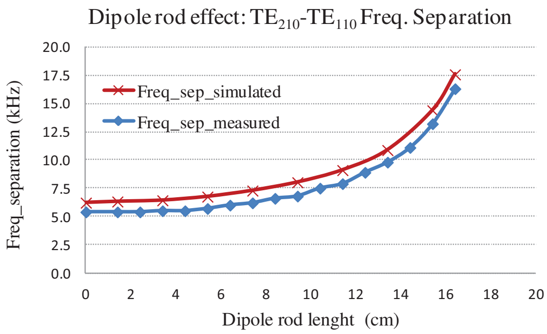


Figure 5: Dipole stabilizer rods effect.

## MECHANICAL ERROR STUDY

As shown in Table 1, a dipole/dipole mode splitting of 2.4 MHz occurs in the RFQ-CM. This can be due to machining tolerance and misalignment issues, as shown in [7] and by dimensional metrology results. To better understand this effect, a set of simulations have been carried out to demonstrate the relation between misalignment errors in the vanes assembly and the frequency response of the RFQ-CM.

One example of the studied cases, where only one vane is equally shifted in both x and y directions, is plotted in Figure 6. It can be observed that while one of the dipole modes is barely affected, the quadrupole mode and the other dipole mode closes to each other, thus risking the right operation of the RFQ-CM.

A second evidence of the misalignment of the vanes and manufacturing mechanical error is the field flatness response of the magnetic field. By using a bead-pull test-bench, fully designed and implemented at ESS-Bilbao [8], Figure 7 shows the normalized magnetic field measured at each of the four quadrants of the RFQ-CM. As it can be seen, two quadrants follow quite accurately the simulated field profile, while the other two show a worse field flatness, thus clearly indicating that the vanes are not properly aligned.

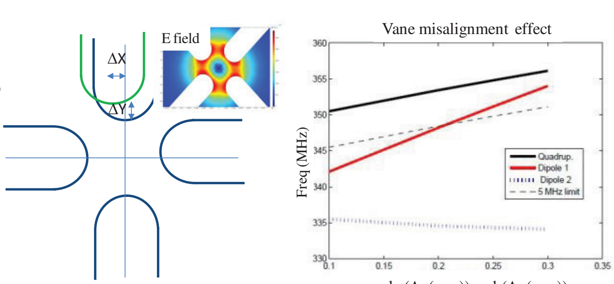


Figure 6: Vane misalignment study.

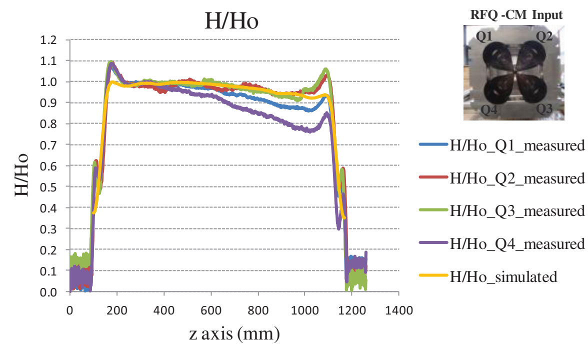


Figure 7: Magnetic field normalized profile.

## CONCLUSIONS

In general terms, the behaviour of the measured figures of merit of the RFQ-CM agrees well with the numerical simulations.

The measurement discrepancies found, in the resonant frequency, dipole mode splitting and field profile, are due to the mechanical errors in the vane manufacturing as well as misalignment issues in the cavity assembly. The performance of the dipole stabilizer rods and the tuners have also been experimentally validated, quantifying their effect on the Qo degradation. Finally, the incorporation of RF seals in the cavity only provides a poor 2.5% improvement in Qo for low power measurements.

## ACKNOWLEDGMENT

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