

RECENT RF AND MECHANICAL DEVELOPMENTS FOR THE ESS RFQ

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Abstract

The ESS Radio-Frequency Quadrupole (RFQ) is a 4-vane resonant cavity designed at the frequency of 352.21 MHz frequency. It must accelerate and bunch a 70 mA proton beams from 75 keV to 3.62 MeV of energy with a 4% duty cycle. The current 3D design evolved and is currently divided in 5 segments for a total length of 4.54 m. This paper presents a complete radiofrequency (RF) analysis using the ANSYS Multiphysics 3D RF simulating code HFSS and a RFQ 4-wire transmission line model (TLM). It describes the integrated cooling strategy based on a coupling between the RF power losses and the thermo-mechanical physics in order to allow a proper RFQ tuning once under operation.

INTRODUCTION

Today's final ESS 4-vanes RFQ design is a 4.54m long, 5-sections resonant cavity including 60 adjustable slugs dedicated to the cavity tuning along with 2 power couplers and 40 ports for pumping and couplers. A review of the ESS-RFQ design status and the scheduled fabrication and testing procedures is presented in [1]. ESS being the latest of the RFQ generation designed and to be commissioned by the CEA-IRFU and delivered at ESS in Lund, Sweden, the 4 steps development strategy detailed in [2] was applied. In this paper, only the steps related to the 2D and 3D RF design and thermal structural optimization of the cavity are presented. The focus is given on the multiphysics workflow established between the RF study in both 2D and 3D models and the thermal mechanical analyses with COMSOL (v3.5) and ANSYS (v14.5) workbench platform.

RF & THERMO-MECHANICAL STUDIES OF THE RFQ CAVITY

RF Optimization and Thermal Management

2D RF calculations were mainly used to optimize the RFQ cross section along the beam axis. Early on, the design targeted a constant vane radius with non-constant ramped voltage and consequently, a non-constant modulation mean value and cavity height (Figure 1). The 3D RF results led to the optimization of the vane end-circuits, tuning slugs, end plate rod lengths and the RF power coupler in order to reach the ESS operation specifications. Finally, a TLM was constructed based on those RF calculations in order to specify the tuning range capabilities of the slugs in correlation with the manufacturing tolerances imposed for the final design. Further details on this optimization are compiled in the final RF design review report [3].

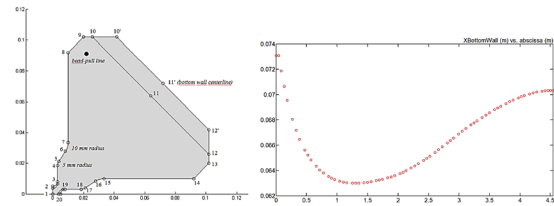


Figure 1: Representation of the ESS-RFQ section with variable cavity back plane height along the beam axis.

The RF power induces a heat deposit in the copper bulk of the RFQ cavity that must be removed through a strategic positioning of cooling channels. The main goal for such cooling system is to limit the cavity deformation and maintain the RFQ frequency and the voltage profile during operation. Although, the cooling strategy for the ESS-RFQ, which is operating under a pulsed-RF mode (nominal duty cycle around 4%; 5% considered in the design phase), is a lesser challenge than continuous wave RFQs such as SPIRAL2, it represents nonetheless an opportunity to verify the workflow between the different numerical tools available for such optimization. Indeed, both COMSOL and ANSYS software provide multiphysics platforms dedicated to studying the coupled effect of RF power dissipation on the structure and reversely the cavity shift in resonance frequency due to the cavity deformation.

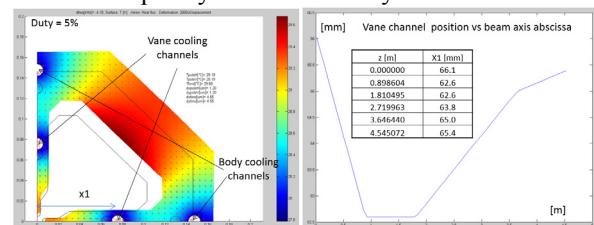


Figure 2: Representation of the 2D deformed section with both channels locations (x_1 =variable position of vane channel).

COMSOL is appropriate for fast 2D RF, thermal and structural coupled calculations. The 2D study allowed the sizing and the positioning of the cooling channels: two separate circuits (both $\varnothing=10$ mm) are implemented per section; one for the vane and one for the body, so that the temperature control is possible on each circuit independently. The design criteria is to get the same frequency with and without RF power. One way to satisfy this criteria is to have the same temperature rise along both channels in order to ensure the same transverse deformation for the vane and the cavity back along the RFQ (Figure 2). Those conditions are achieved with a variable position of the inner channels along the beam axis. It is to be noted that the velocity in those channels is limited to 3.2 m/s and they are located so that a minimum of 5 mm

copper wall separates the water channel from the vacuum of the cavity. This constitutes a precaution against leakage and erosion for the annealed copper at high temperature.

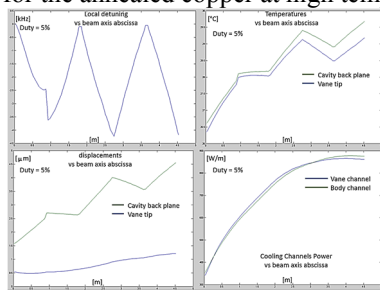


Figure 3: 2D optimization results: Detuning, temperature profile, displacement and power dissipation/channel.

Figure 3 illustrates the cavity detuning (-5 kHz accepted) and the corresponding radial displacement of the characteristics lines; the vane tip < 1.5 μm and cavity back plane < 5 μm along the RFQ. This represents a constant ratio of 3 between those two key displacements.

Transition to 3D RF/Thermomechanical Models

The 3D calculations are based on a quarter geometry of the RFQ using 2-planes symmetry (RF coupler not implemented). In order to use the two-way coupling between ANSYS and HFSS, the original geometry used in HFSS was later on imported in Mechanical (Figure 4).

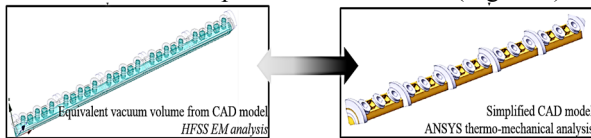


Figure 4: Geometries used in HFSS and ANSYS (1/4 of the RFQ cavity).

Unlike 2D simulations, the 3D model includes all the RFQ components which constitute “discontinuities” along the body of the cavity: the tuning slugs (at nominal depth) and the pumping grids. The vane undercuts and intersections connecting flanges (stainless steel) are also represented. Another important difference between both representations is the channel configuration: in 2D, the channels are modeled as straight through for each section while in effect (3D), they are U-shaped to accommodate the separate hydraulic circulation (view in Figure 5). The vacuum ports are directly brazed on the RFQ body (copper on copper), therefore their cooling is taken care of by the body channels. However, tuners have to be cooled through coaxial tubes connected to an independent circuit since they are mounted thanks to stainless steel flanges (less efficient for heat transfer). The end plates do not require cooling even though the option is integrated within the current design (Figure 5).

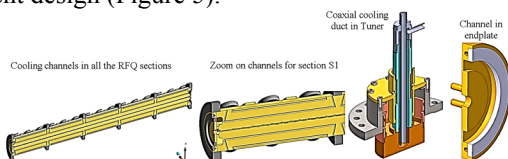


Figure 5: Cooling ducts layout in the cavity body, tuners & endplate.

The power density 3D map is calculated using HFSS. ANSYS enables a direct projection and interpolation from the HFSS mesh on the mechanical mesh of the calculated power density. Two cross-checks can be performed in order to ensure a proper interpolation:

- A mapping quality factor check: provided by ANSYS; shall be close to 1. This is a rigid constraint since it requires the electromagnetic mesh to be equivalent in quality to the mechanical and/or thermal mesh even though the physics and the volumes are not the same (Figure 6).

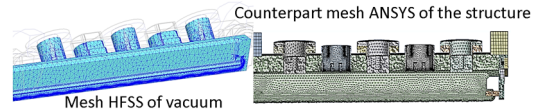


Figure 6: View of the meshes in vacuum (HFSS) and in the structure.

- A total power check: the total RF power calculated with HFSS shall be the same as the total heat removed by convection through all cooling components. The scaled power dissipated in the ESS-RFQ is about 10.5 kW (Figure 7) and it is coincident between both calculations (<1%).

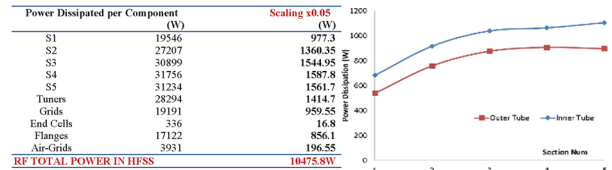


Figure 7: Power per component from ANSYS-HFSS (5% duty cycle) and per channel in RFQ in thermal calculation (tuners values not reported).

With the 3D model, the power dissipation in the body and vane ducts are no longer the same per section since the “vane” circuit is actually longer (Figure 7).

3D Thermal & Structural Simulations

An estimate of the heat transfer coefficient based on Colburn empirical equation was given as an input for the 3D modeling ($h=13,000 \text{ W/m}^2 \cdot \text{°C}$). ANSYS-Fluent was used to verify the uniform distribution of this coefficient set in both channels (Figure 8).

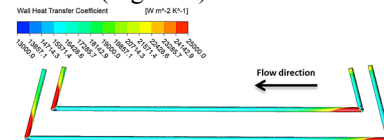
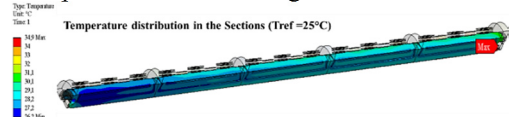


Figure 8: Heat transfer coefficient in channels (ANSYS Fluent).

The temperature distribution in the RFQ cavity and its components is illustrated in Figure 9. The maximum temperature in the RFQ body corresponds to the high energy region coinciding with the vane undercut. It is also the farthest point from the cooling vane duct.



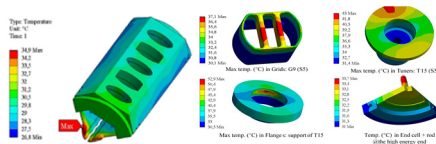


Figure 9: The temperature distribution in the RFQ and its components.

A maximum temperature rise of 0.85° C shall be expected in the water (for each vane channel at section 5).

The thermal load induces the deformation of the RFQ cavity. Ideally, this displacement should be projected through the workbench interface on the HFSS mesh in order to compute directly the cavity detuning (this point will be discussed later). However, we have chosen to check the total cavity deformation and to validate the design by using the following design rules from the 2D study:

- A ratio of 3 between the cavity back plane and the vane tip radial displacements.
- A maximum radial displacement of ~10 μm at the key lines.

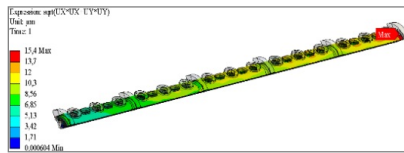


Figure 10: Radial displacement within the body of the RFQ.

Figure 10 and Figure 11 illustrate the cavity radial deformations under the calculated thermal load. The maximum displacement is well bounded and under 10 μm. The ratio between the electrode tip and the cavity wall is on average 2.8 which is considered satisfying as well. Indeed, during operation, temperature regulation per channel will allow finer tuning of the resonant cavity.

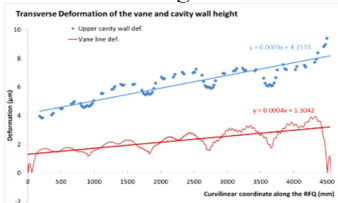


Figure 11: Radial displacement at the vane tip and the cavity upper wall.

The longitudinal expansion of the RFQ reaches ±160 μm (fixed at the center) which have little effect on the frequency. However, it is taken into account in the mechanical supports of the RFQ so that they can slide without friction along that range. The heat load effect on the deformation of each tuner slug can also be computed (Figure 12). However, the relevant estimates of those deformation are known only once the RF calculation is made with the final positioning of the slugs.

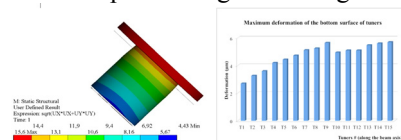


Figure 12: Tuner average transverse displacement.

The mechanical stress has to be evaluated within the RFQ structure because of the low yield strength of the annealed copper (35 MPa). It is seen in Figure 13 that the local equivalent Von Mises stress does not exceed 13 MPa.

Sensitivity to various parameters such as material properties, heat transfer coefficient and local temperature rise in the water ducts were checked to validate the final design [4].

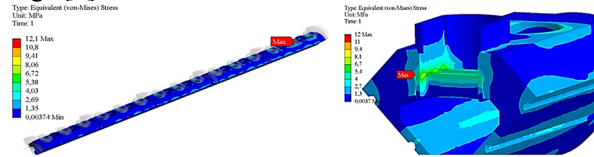


Figure 13: Equivalent stress in the copper body of the RFQ cavity.

DISCUSSION

The “new” capability of the ANSYS software to perform coupled numerical simulations in 3D between multiphysics solvers for the RF/thermal/mechanical is discussed here in terms of precaution and reliability for components such as a resonant cavity:

- HFSS => ANSYS: the difficulty in this step is to be able to check “independently” that the power density interpolation is well performed. This will allow us to not rely of the mapping quality factor which is an abstract notion. Besides, as illustrated in Figure 14, HFSS calculations present “hotspots” that have no physical origin. Being able to extract the power density independently and manipulate the data by using a cutoff on those hotspots and controlling the mesh is the objective for post-processing script for HFSS results data.

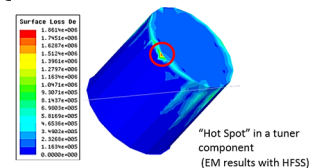


Figure 14: HFSS results with illustration of “hotspot”.

- ANSYS=>HFSS: The RFQ displacements are within the ~10 μm hence, projecting those on a the HFSS mesh through the workbench automatic routine cannot allow us to discriminate the frequency shift due to numerical systematic errors and/or the physical detuning. More testing is necessary to better understand this step within ANSYS (effect of mesh and elements used, deformed geometry reconstruction) and validation will be performed using the Slater analytical method.

CONCLUSION

CEA-IRFU has developed an expertise in designing 4 vanes RFQs. In order to achieve both the RF and thermo-mechanical optimum designs for such cavities; we continue to constantly integrate and challenge the latest numerical capabilities. The ESS-RFQ design presented the opportunity to implement a possible 3D workflow to study those coupled effects.

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