# 3D THERMO MECHANICAL STUDY ON IFMIF-EVEDA RFQ

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*Abstract*

In the framework of the IFMIF/EVEDA project, the RFQ is a 9.8 m long cavity, with very challenging mechanicals specifications. In the base line design, the accelerator tank is composed of 18 modules that are flanged together. An RFQ prototype, composed of 2 modules with a reduced length, aimed at testing all the mechanical construction procedure is under construction. In this paper, the thermo-mechanical study by means of 2D thermo structural and 3D fluid-thermal-structural simulations will be described. The measurements made with a cooling water circuit on a part of the RFQ prototype and the comparison with fluid thermal simulation will be reported.

## THE IFMIF-EVEDA RFQ COOLING LAYOUT

The RFQ is realized in 3 supermodules (6 modules each) and every supermodule is composed of 2 cooling modules of 3 modules each. The cooling channels of each supermodule are not connected with the cooling channels of adjacent ones. The total RF power to be removed by the cooling system amounts to 708 kW. The cooling system layout (Figure 1), with water inlet at the extremes of the supermodule and three modules in series maintains certain periodicity for the temperature distribution.

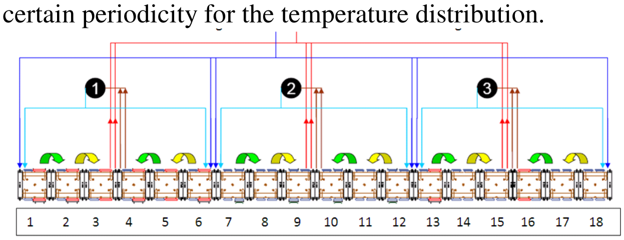


Figure 1: Cooling system layout of IFMIF-EVEDA RFQ.

Due to the fact that the RFQ voltage is ramped, the RF power is increasing from the low energy to the high energy super modules (Figure 2). These values are calculated as the 2D RF dissipation multiplied by 1.3 for 3D details and by 1.21 to allow working 10% above the nominal field.

The main goals of the RFQ cooling system are:

- Removing power from the whole structure
- Regulating the resonance frequency during steady state operation
- Guaranteeing longitudinal voltage uniformity at each power level

In particular a tuning range of [-100;+100] kHz around the nominal frequency of 175 MHz has to be guaranteed. The cooling system provides two separate circuits on each "supermodule", one for vanes and one for vessel. The temperature of the inlets of the vanes ducts is fixed to 15 °C, while the inlets of the vessel vary in a range of [15;27] °C. The nominal velocity considered on each channel was 3 m/s. The goal is to reach -100 kHz with all the inlets at 15 °C, and the +100 kHz with the increasing of the inlets of the vessel to 27 °C.

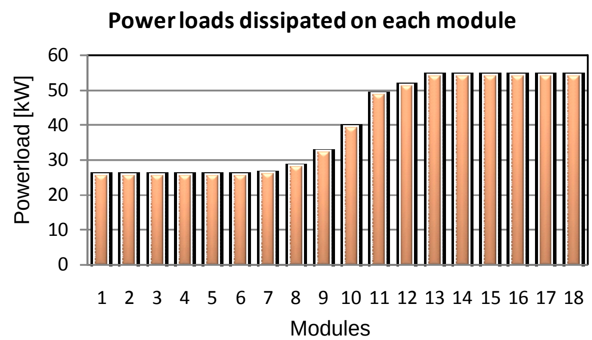


Figure 2: Dissipated power in the RFQ modules.

## COOLING DUCTS LAYOUT

The choice of replacing the "threaded" cooling ducts with "smooth" ones was previously presented. In fact a non-uniformity of the flow along the ducts occurs [1]. The layout of the cooling channels in terms of number, positioning and diameter varies from module to module and it was decided by means of preliminary 2D thermo structural analyses and more accurate 3D fluid dynamics structural and thermal simulations. All analyses were performed with ANSYS 12 package.

## 2D THERMAL STRUCTURAL SIMULATIONS

2D thermal structural analyses were performed in order to obtain a preliminary configuration of the cooling ducts layout. The 2D temperature distribution for the cross section of the last six modules is shown in Figure 3

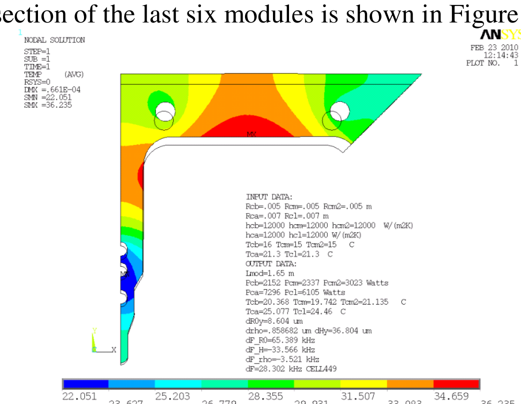


Figure 3: 2D temperature distribution for a temperature of 15 °C for vane and 22 °C for the vessel cooling ducts.

The induced deformation of the transverse RFQ sections produces a shift δf of the $TE_{21}$ cut-off frequency that can be calculated with the Slater formula [2]. An accurate approximation of such shift can be given by simply determining the corresponding variation of the, mean aperture $R_0$, of the pole tip radius ρ and of the of the upper wall height with respect to beam axis H, with the relationship

$$\delta f = \alpha_{R0}\delta R_0 + \alpha_\rho \delta\rho + \alpha_H \delta H \quad (1)$$

In general $\alpha_{R0}$, $\alpha_\rho$, $\alpha_H$ are different for each RFQ module, In the following table their values for the initial and final RFQ cells are reported.

Table 1:The $\alpha_{R0}$, $\alpha_\rho$, $\alpha_H$ coefficients

| Module | $\alpha_{R0}$ [MHz/mm] | $\alpha_\rho$ [MHz/mm] | $\alpha_H$ [MHz/mm] |
|---|---|---|---|
| 1 to 6 | 11.3 | -5.3 | -1.2 |
| 13 to 18 | 7.6 | -4.1 | -0.9 |

The cooling channels are optimized so to minimize the cut off frequency shift between RF on and RF off, at the beginning and at the end of the cooling channel (water inlet and outlet). Moreover, by keeping cold the vanes channel and varying the vessel channels temperature the necessary cooling range is obtained.

## 3D SIMULATIONS

Due to the fact that transverse and longitudinal dimension of the modules are comparable, 3D simulations were necessary to evaluate the effects of the following details on the entire modules, as in Figure.4:

- The holes for tuners and for vacuum port;
- Presence of steel flanges;

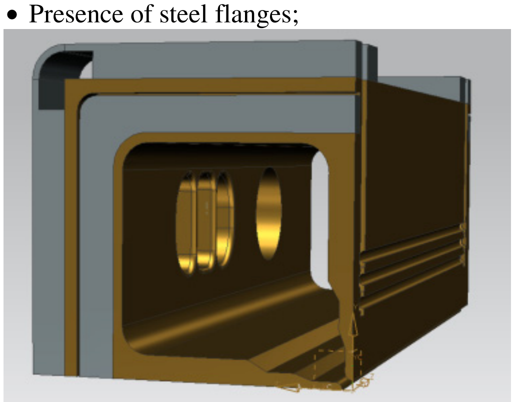

Figure 4: Layout of the module 16.

Three dimensional integrated fluid-thermal-structural simulations were performed in order to take into account directly and to calculate accurately heat exchange between cooling fluid and the module.

First of all, since a single manifold that feeds all the vane cooling ducts was considered, simple fluid dynamics simulations were performed to dimension it for the last supermodule. In fact, due to the relatively short length of each mechanical module, a different arrangement would have led to predominant 3D effects, without any effective gain in cooling efficiency. At this point the goal was to dimension the diameter of the manifold and of the ducts in order to divide the flow as more uniformly as possible.

Next step was the integrated thermal structural fluid dynamics analyses, thus calculating the deformation of the entire module, as in Figures 5 and 6. The temperature on the pole tip is mostly uniform and its deformation is in a range of 10 µm.

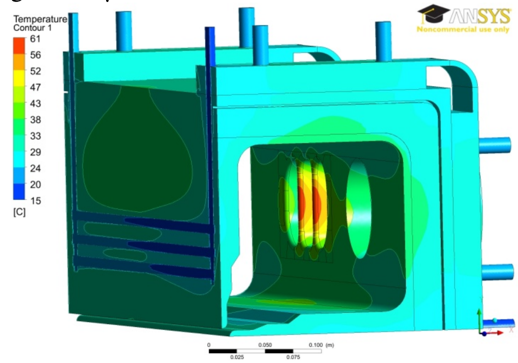


Figure 5: Temperature on 3D module 13 for an input water temperature of 15 °C for vane and 22 °C vessel cooling ducts.

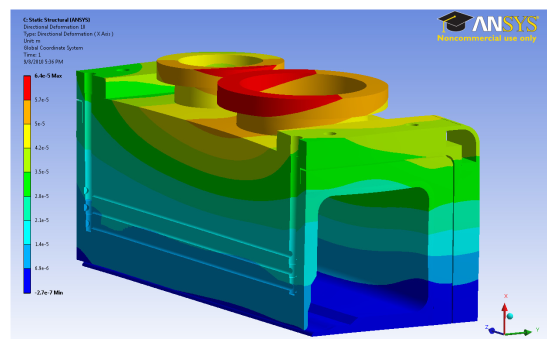


Figure 6: 3D y-deformation on module 13 for an input water temperature of 15 °C for vane and 22 °C vessel cooling ducts.

As for 2D analyses, power loads were derived from SUPERFISH calculations and 3D details (i.e. tuner holes and vacuum grids) were simulated with Ansoft HFSS [3]. Then the calculation of the frequency shift was possible by using Equation (1) the entire length of the modules.

Since the whole RFQ has to be tuned for a range of ± 100 kHz, each cooling module has to guarantee that range. It was necessary to merge the simulations of each of these modules, for example by taking the output temperatures of the channels of module 13 as the input temperatures of module 14 and so on.

The pattern of the $TE_{21}$ cut-off frequency shift due to the above-mentioned deformation is shown in Figure 7.

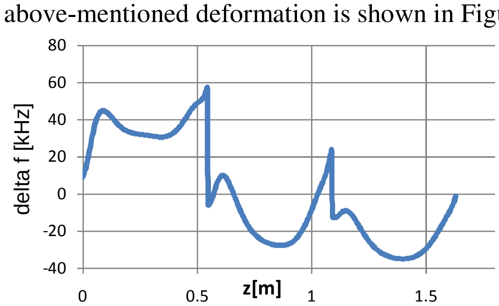


Figure 7: Frequency perturbation on modules 13, 14 and 15 for the tuned case, i.e. Tv=15 °C and Tf=22 °C.

The effect of such frequency perturbation on the voltage uniformity can be calculated with a perturbation approach [4] and it results being negligible respect to the ±2% specifications driven by beam dynamics (Figure 8). This effect was calculated by assuming a constant section RFQ and by replicating the profile of Figure 6 on all the 6 cooling modules.

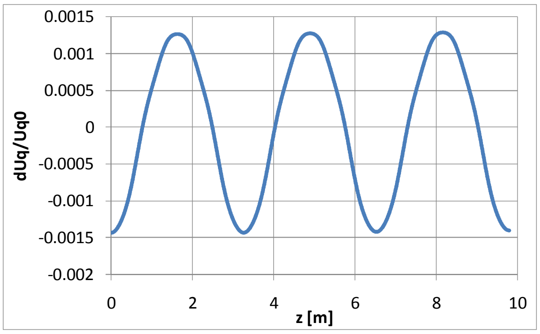


Figure 8: the voltage perturbation during high power operation.

A comparison of 2D and 3D thermo-structural simulation results has been made, in order to check the validity of the 2D initial design considerations.

For the module 13 the agreement is quite good, at low temperatures in the vessel, but at high temperature on the vessel the difference is a bit larger, 40 kHz. In the 3D case a range of +/- 100 kHz is guaranteed.

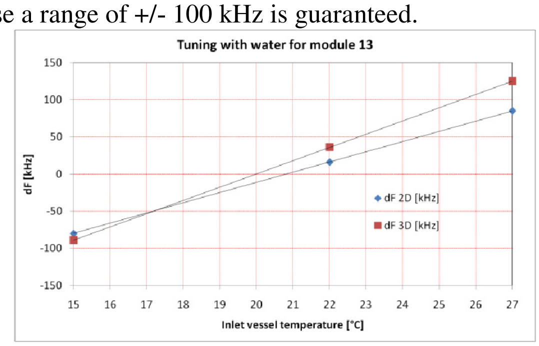


Figure 9: Frequency range on module 13, for a vane temperature of 15 °C as function of vessel temperature.

## EXPERIMENTAL RESULTS

An experimental setup, using an EDM copper vane of the mechanical prototype [1], has been made to check:

- The heat exchange coefficients of ducts;
- The validity of ANSYS-CFX thermal-fluid simulations;
- The water pressure drops on the ducts.

The apparatus was composed of the copper piece, heat resistors of able to produce a heat flux of about 4 W/cm2 on vane surfaces, a cooling water circuit and an infrared thermal camera, Figure 10. A mass flow of about 21 l/min with a average temperature of 15 °C was pumped in the vane cooling ducts.

The experimental heat exchange obtained was 11500 W/m2K, and it was used in the simulation of the RFQ cooling channel [1]. A similar result has been obtained with CFX analyses. Because of different values of emissivity on the component, the actual temperature was measured in particular zones, Figure 11. The temperature distribution calculated with CFX is reported in Figure 12. The accordance between experimental results with calculated ones is discrete, as in Figure 13. The water pressure drop confirmed the expected value of about 0.26 bar.

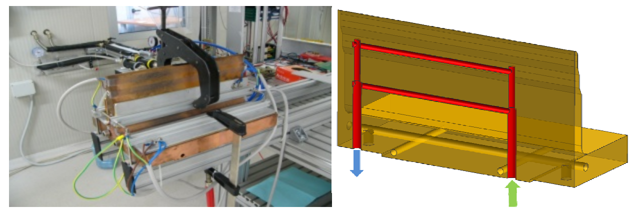

Figure 10: Layout of the cooling test system.

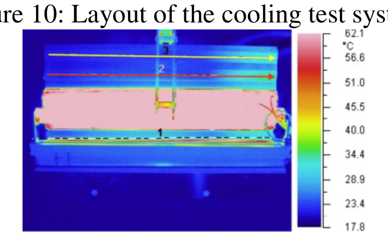


Figure 11: Infrared measured temperature distribution.

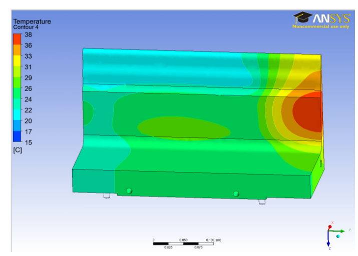


Figure 12: CFX thermal map [°C].

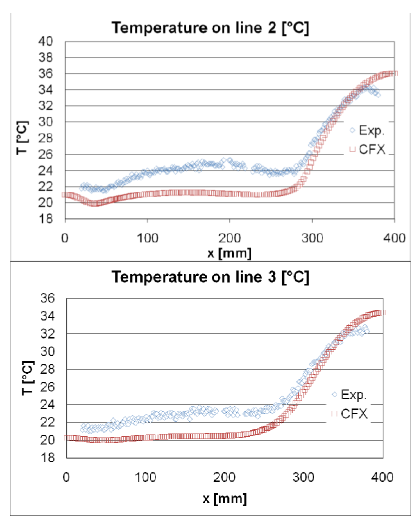


Figure 13: Temperature along the vane, from experimental and CFX simulation.

## REFERENCES

[1] A. Pepato et al., IPAC2010 Kyoto(Japan) p. 600.
[2] A. Palmieri LNL Annual Report 2008 p.231.
[3] A. Palmieri et al., these proceedings.
[4] A. Palmieri et al. IPAC2010 Kyoto(Japan) p. 606.