THERMO-MECHANICAL CALCULATIONS FOR THE SPES RFQ

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Abstract

Within the SPES project at INFN-LNL[1] a new injection line will be built at INFN LNL [2]in order to transport and match the RIBs to the existing ALPI superconducting linac. This line includes a new RFQ that will operate in a CW mode (100% duty factor) at the operating frequency of 80 MHz. The RFQ is composed of 6 modules about 1.2 m long each. Each module is basically composed of a Stainless Steel Tank (AISI LN 304) and four OFE Copper Electrodes. A copper layer will be electrodeposited on the tank inner surface and a spring joint between tank and electrode is used in order to seal the RF. Moreover, the electrodes are equipped with two brazed SS inserts in order to allow coupling with the tank. In order to remove the RF power (about 100 kW) as well as to allow frequency control during high power operation for a given cooling channel layout, a set of thermo-structural simulations was performed, whose input data were the RF Power densities calculated with 2D and 3D codes. In this paper the analytical and numerical methods used, as well as the main outcomes of these studies are presented.

THE SPES RFQ

The SPES RFQ is designed in order to accelerate beams in CW with A/q ratios from 3 to 7 from the Charge Breeder through the MRMS and the selection and injection lines up to the MEBT. The main parameters of the RFQ are listed in Table 1:

Table 1: Main RFQ Parameters

Paramater [units]	**Design value**
Frequency [MHz]	80
In/out. Energy [keV/u]	5.7-727 (β=0.0035-0.0359)
Accelerated beam current [μA]	100
Inter-vane voltage V [kV, A/q=7]	63.8 – 85.84
Vane length L [m]	6.95
Average radius R_0 [mm]	5.27÷ 7.89
Synchronous phase (deg.)	-90 ÷ -20
Focusing Strength B	4.7 ÷ 4
Pole tip radius ρ	4.01÷5.97 (0.76 R_0)
Stored Energy [J]	2.87
RF Power [kW] (30% margin)	98
Q value (30% margin)	14000
Max power density [W/cm^2]	0.31 (2D), 11 (3D)

The voltage law is a linear function along z $V(z)=V(0)+a\cdot z$ with a=3.177 kV/m and V(0) depending on the A/q of the ion to be accelerated. Such law is implemented by designing the RFQ in order to obtain a constant TE_{21} cut-off frequency fc=79.5 MHz along the structure and by properly shaping the vane undercuts at the Low and High Energy Ends of the RFQ. This choice sets the tuner tuning range of the RFQ in the interval [79.5 MHz, 80.5 MHz]. In order to compensate the R_0 variations, the capacitive region is varied along the RFQ (Fig.1). Therefore the electrode thickness is constant and equal to 48 mm and the tank inner radius R is equal to 377 mm.

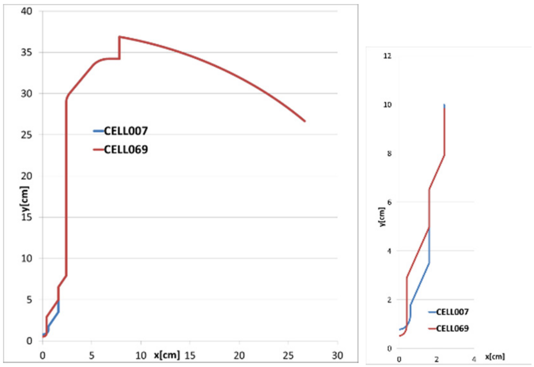

Figure 1: Capacitive tuning of the RFQ sections corresponding to the highest (Cell007) and lowest (Cell069) R_0 values.

The RFQ Cooling system is designed to remove power and to finely tune the cavity resonant frequency during operation by temperature regulation. For such a purpose, it is necessary to have two independent water loops with two temperature set points: a "cold" circuit for the tank, and a "warm" one for the vanes. By mixing with a 3-way valve the cold inlet water with part of the warm water coming from the cavity, it is possible to vary the resonant frequency of the RFQ and to tune the cavity accordingly. Therefore a thorough thermo-structural analysis of the RFQ is needed in order to determine, for s given cooling channel layout and inlet temperature, the associated temperature and displacement fields in the RFQ as well as the mechanical stresses. The outcomes of this analysis are the frequency sensitivities vs water temperatures and/or RF input powers in order to determine the actual tuning range with water temperature during RFQ operation. This analysis was carried out both in 2D (SUPERFISH) for the input parameters (power densities) and in 3D (ANSYS Electromagnetic Suite and ANSYS 16).

Preliminary simulations permitted to determine the position of the cooling channel and the cooling water path arrangements (Figs. 2 and 3) and the water input temperatures for vane and tank. It is important to notice two main aspects of this RFQ: first, the vane and the tank are thermally insulated and second the RF power balance is approximately 60% on the vanes (Cu) and 40% on the tank (SS). The channel radii are Rc_2= 6 mm on the vane and Rc_1=4 mm on the tank, the inlet water velocity is 3 m/s and consequently the heat convection coefficient h_c was chosen to be equal to 10000 $W/m^2 \cdot K$. For the reference case study the inlet vane temperature (T_2) is 20°C and the inlet tank temperature (T_1) is 15°C. The channel heights on the vane are 125 mm (90 mm for the 1st and 6th module) and 305 mm, while the channel angles on the tank with respect to the electrode symmetry plane are 15° and 33° respectively (Fig.2).

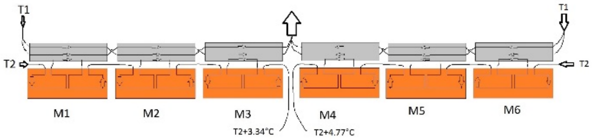

Figure 2: Cooling channel connections.

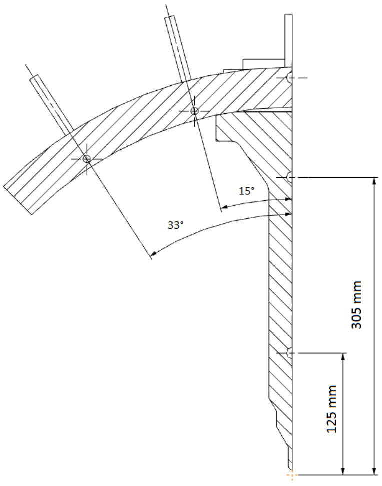

Figure 3: Transverse cooling channel layout.

From the above figures, it is possible to notice that

- The vane and tank channels are connected in series from modules 1 to 3 and then from modules 6 to 4.
- In order to reduce the thermal stress on the adaptation piece between tank and electrode, an additional cooling channel on the tank is foreseen with same radius inlet temperature of the vane ones.

As for the water temperature calculations to be used as input data for thermo-structural calculations, they were derived from the knowledge of the power per unit length $p_{d2}(z)$ [p_{d1} (z)] on the vane [tank] [W/m] via the relationship

$$T_{out\,1[2]} = T_{in[2]} + (1/\dot{m}c_p)\int_{z_{in}}^{z_{out}} p_{d1[2]}(z)dz \quad (1)$$

T_{in} [T_{out}] being the inlet [outlet] water temperatures, $\dot{m}$ the mass flow rate and c_p the water specific heat.

2D CALCULATIONS

2D calculations were performed in order to determine, via the SUPERFISH code, the input power densities to be inserted in the thermo-structural 3D simulations. For such a purpose 21 significant RFQ section (1/4 of RFQ) were taken into account and the related power densities were calculated. Moreover, from the same simulations, the frequency sensitivities vs. R_0 and R variations were determined. In particular, the dissipated power per unit length profile p_{dSF} [W/m] is calculated as.

$$p_{dSF}(z) = \oint_{\gamma} p_{densSF}(z,s)ds \quad (2)$$

$p_{densSF}(s,z)$ being the surface power density [W/m^2] given by the code and γ is the RFQ profile.

In the following figure 4 such profile is shown and it is compared with the scaling law $p_d(z)=p_d(0)(V(z)/V(0))^2$.

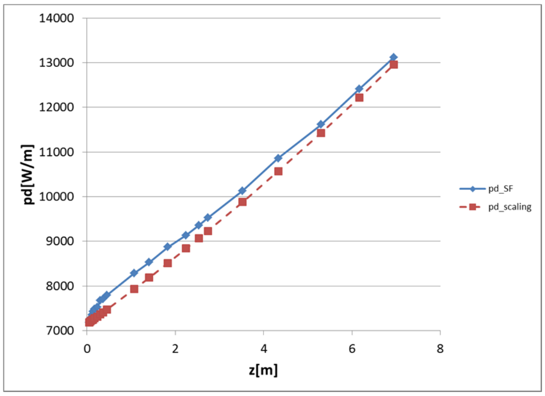

Figure 4: Comparison between the pd(z) functions given by SUPERFISH (solid curve) and the scaling law (dotted curve).

Now, since the differences between the two calculations are below 5%, this scaling law will be used for the input surface power densities for thermal calculations.

As for frequency sensitivities is concerned, it results that $\chi_{R0}=\partial f/\partial R_0$ varies from 2.5 MHz/mm to 3.7 MHz/mm (average value 3.3 MHz/mm) and $\chi_R=\partial f/\partial R$=-0.2 MHz/mm. The frequency shift can be calculated as $\Delta f=\chi_{R0}\Delta R_0 + +\chi_R\Delta R \approx =\chi_{R0}\Delta R_0$ (in most cases the second term can be neglected).

3D CALCULATIONS

The 3D simulations were performed with the ANSYS Workbench v.15 software on 1/8 of the overall RFQ, including, brazed inserts and vane undercuts. Such simulations consisted in stationary thermal and structural calculations. The Power densities from the electromagnetic solver were used as an input for the thermal calculation. Finally, from the knowledge of the deformation profile, it was possible to determine the frequency shift. In these simulations the simplified assumption that each channel of the vanes and of the tank absorbs the same amount of power respectively was made. In particular, input data power densities p_{dens} [W/cm^2] were given by SUPERFISH at each RFQ section according to the scaling law introduced in the preceding paragraph. Indeed, on the vane undercuts the power densities were calculated with ANSYS Electromagnetic Suite v 16.1. The average and outlet temperatures for each channel were determined according to (1). Then, from temperature distribution on the RFQ bulk, the corresponding deformation and stress fields were calculated. In this simulation 1'800'000 nodes, 1'100'000 and Tethraedral elements were set, for the Thermal steady state and static Structural.

In Fig.5 the temperature distribution on the RFQ is shown.

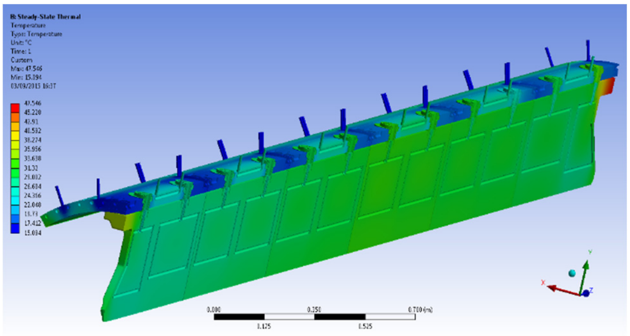

Figure 5: Temperature distribution on the 1/8 of the RFQ. The maximum value of 48°C occurs on the tank in the plane between electrodes at the High Energy side.

As for the deformation pattern is concerned, in the following figure the $\Delta R_0(z)$ deformation is shown for the case T_1=15°C, T_2=20°C.

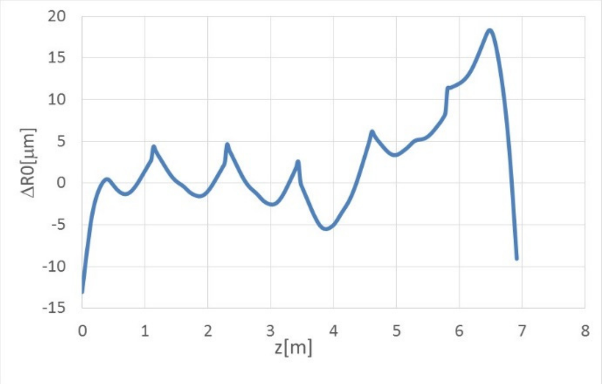

Figure 6: Average aperture perturbation for the case study (vane undercuts included).

This perturbation provokes a frequency shift of 7 kHz and a voltage perturbation $|\Delta V(z)/V(z)|<0.005$, to be compared with the maximum admittable value of 0.03, as for beam dynamics specifications. The frequency temperature sensitivity in this case was investigated as well. The vane temperature coefficient $\partial f/\partial T_2$ is equal to about -17 kHz/°C. Moreover the frequency shift $\Delta f_{on\text{-}off}$ from maximum input power to zero input power is +85 kHz, and the vane+tank temperature coefficient $\partial f/\partial T_{1,2}$ (that is the frequency shift due to both T_1 and T_2 increase is -2kHz/°C. Therefore a temperature tuning range of about ±85 kHz can be established for a T_2 variation in the range [15°C, 25°C]. Moreover, as power increases frequency increases, as well as water temperature. Nevertheless, since $\partial f/\partial T_{1,2}<0$, then a stabilizing mechanism is established and a thermal runaway is avoided. This phenomenon is similar to the one encountered both for TRASCO [3] and IFMIF [4] RFQs.

Finally, the behaviour of the Von Mises Stress σ_{eqVM} was studied, with particular reference to the effect of the additional cooling channel on the vane. In particular, the $\sigma_{eqVM}(z)$ function was evaluated on a path between two consecutive adaptation piece between tank and electrode on Module #4, considering different values of the product $\Pi_c=A_C\cdot h_c$, $A_c=2\pi l_c R_{C1}$ being the channel surface (l_c = =channel length). The results are shown in Fig. 7 in the case T_1=15°C, T_2=25°C

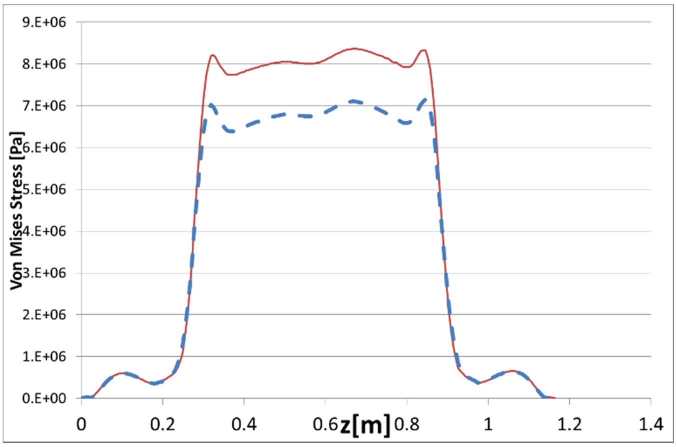

Figure 7: The von Mises stress for hc=0 (solid line) and hc=10000 W/m^2·K (dotted line).

From this figure it is possible to notice that actually the σ_{eqVM} decreases with Π_c, moreover the maximum value is kept below the safe limit of 20 MPa in any RFQ point.

CONCLUSIONS

The outcomes of the combined Electromagnetic and thermo-structural studies validate the current channel layout. Further refinement in this study include the precise pointwise determination of the water temperatures via the usage of the 1D Fluid thermal elements [5].

REFERENCES

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