INFN Laboratori Nazionali di Legnaro

SPES exotic beams for science

THERMO-MECHANICAL CALCULATIONS FOR THE SPES RFQ

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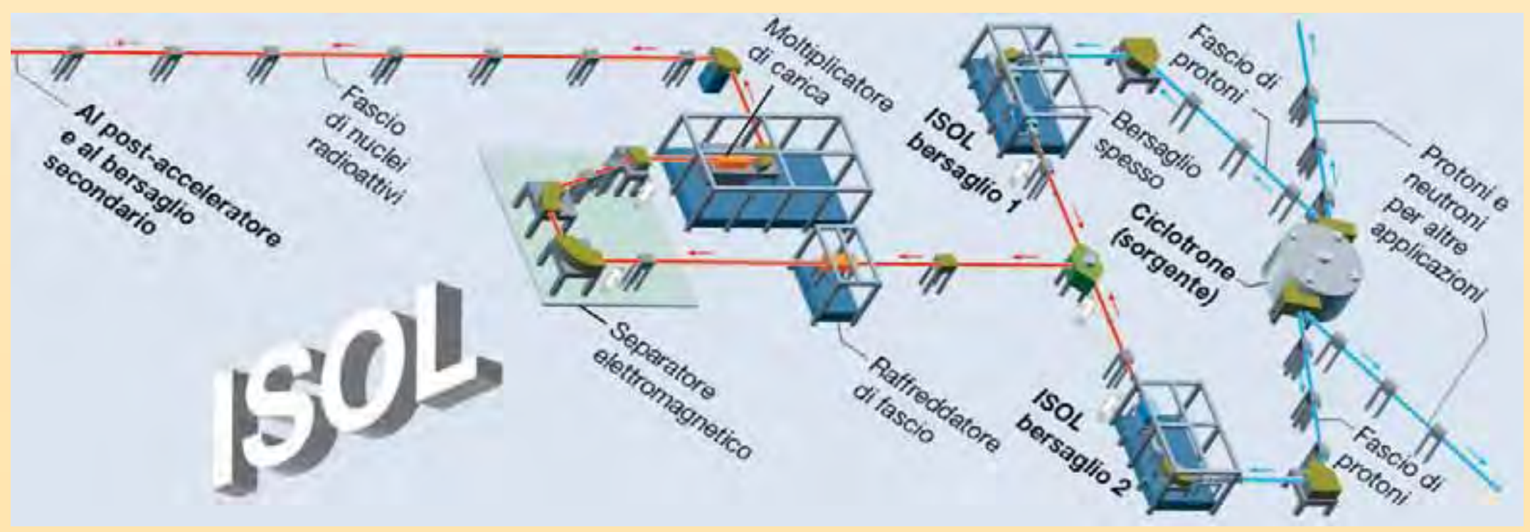
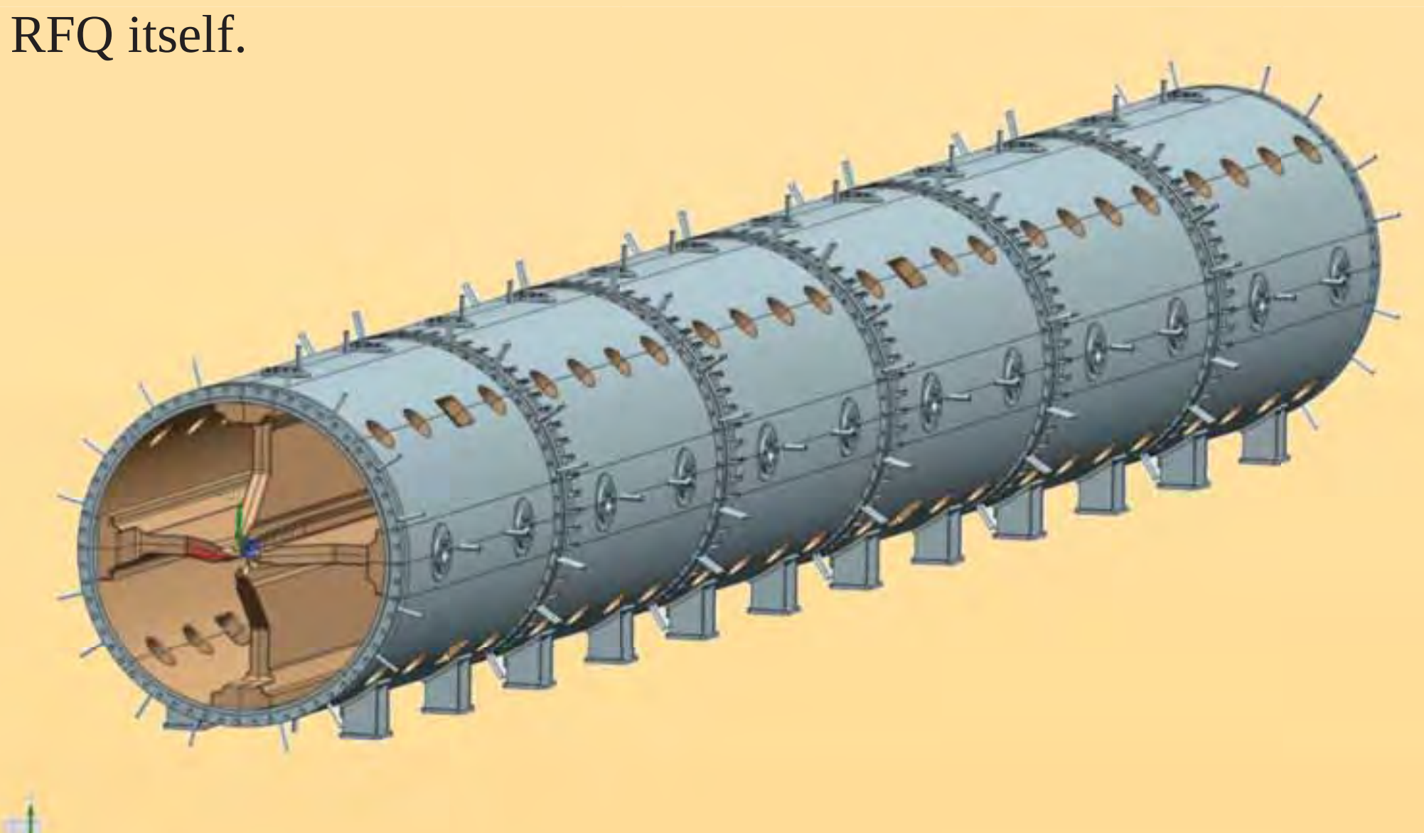
In the framework of the SPES project at LNL a four-vane RFQ (Radio Frequency Quadrupole) operating at 80 MHz, composed of a cylindrical SS tank with Cu plating on the inner surface loaded with four Cu electrodes, is foreseen. The 100kW RF power removal and the frequency tuning with water temperature are accomplished with a system of water cooling pipes. Therefore, a stationary numerical model in the ANSYS Mechanical environment is conceived in order to calculate the RFQ geometry displacements. Tetrahedral elements for Thermo-Structural calculations, coupled with thermal flow elements as well as analytical results for turbulent flow convection calculations are used. The boundary conditions include thermal loads from the Electro Magnetic cavity simulations, as well as atmospheric pressure. The main results in terms of local and global frequency variations vs. both channel inlet water temperatures and the amount of RF power dissipated in the cavity will be presented.

THE SPES PROJECT AND ITS RFQ

The SPES Project is under realization at the INFN Legnaro National Laboratories site. The SPES Project main goal is to provide a production and acceleration system of exotic beams in order to perform forefront research in nuclear physics by studying nuclei far from stability. The SPES Project is focused on the production of neutron-rich radioactive nuclei with mass in the range 80-160. The final energy of the radioactive beams on target will range from few MeV/u up to 11 MeV/u for A=130. The SPES building blocks are: a primary proton accelerator, an ISOL (Isotope Separation On Line) source, the beam selection, transport line and the first part of the secondary beam accelerator needed as injector in the existing LNL superconducting accelerator.

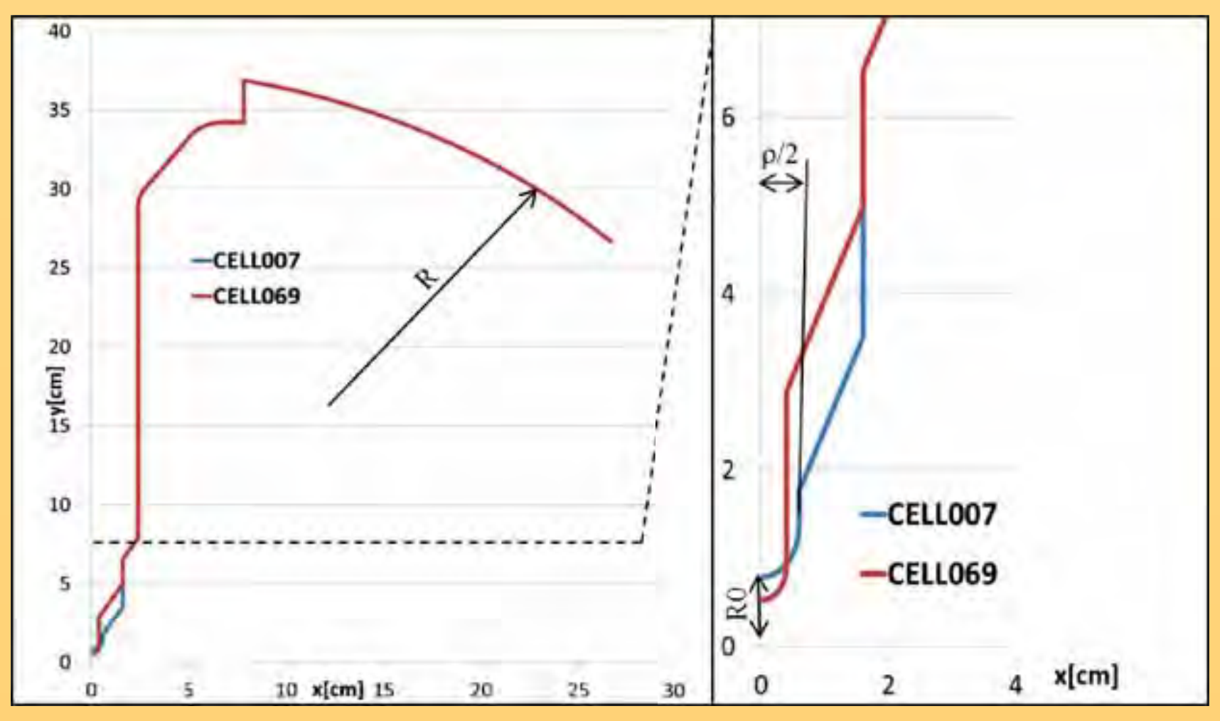


Such injector consists basically of a four-vane RFQ (Radio Frequency Quadrupole) cavity composed of a cylindrical SS tank with Cu plating on the inner surface loaded with four Cu electrodes operating at 80 MHz for an input energy of 5.7 keV/u (keV per nucleon), with output energy of 727 keV/u and charge to mass ratio q/A<= 1/7.In order to properly accelerate the RIBs, the RFQ needs to be fed with an input power in the order of 100 kW CW, the almost entirety of which is dissipated on the Copper walls of the RFQ itself.



Parameters [units]	Design value
Frequency [MHz]	80±0.5
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 R0 [mm]	5.27÷ 7.89
Pole tip radius ρ	4.01÷5.97 (0.76 R0)
RF Power [kW] (30% margin)	98

The removal of such amount of power is accomplished with a system of water cooling pipes. Moreover, since the RFQ has to keep its resonant frequency during its nominal operating regime, the water cooling system has also to ensure the proper deformation pattern of the electrodes and of the tank, in order to allow frequency tuning with water temperature. For such a purpose, a stationary numerical model, conceived in the ANSYS Mechanical environment, is used in order to calculate the RFQ electrode tip displacements, this zone being the most sensitive to frequency perturbations. The model developed allows the study of RFQ cavity local and global frequency variations vs. both channel inlet water temperatures and the amount of RF power dissipated in the cavity.



The electrode thickness is equal to 48 mm and the tank inner radius R is equal to 377 mm. The frequency shift can be calculated as:

$$\Delta f = \chi_{R0}\,\Delta R_0 + \chi_\rho\,\Delta\rho + \chi_R\,\Delta R \cong \chi_{R0}\Delta R_0$$

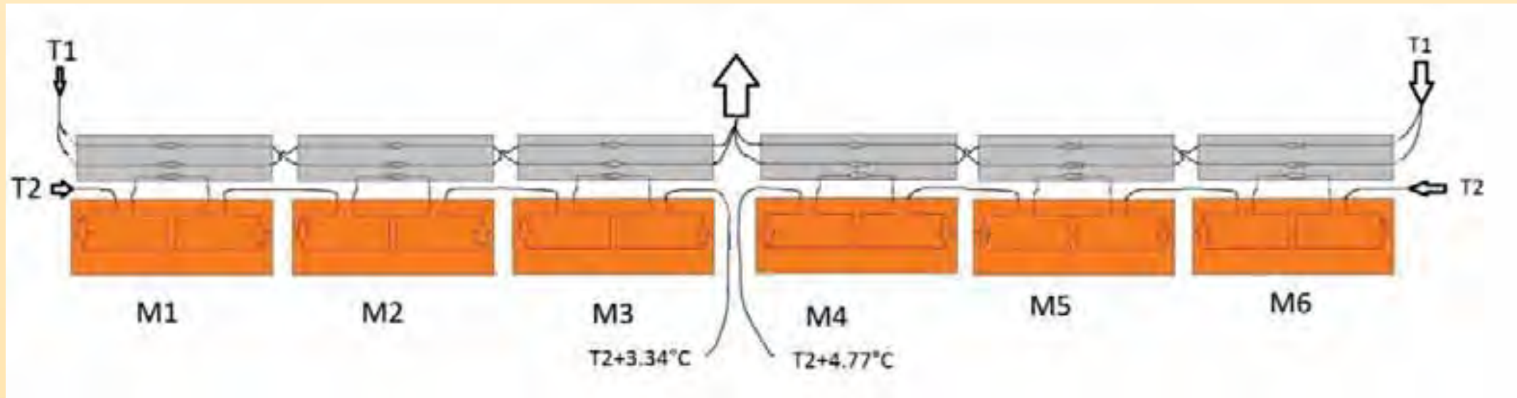
In most cases the second term depends on machining accuracy (10 to 20 μm), the third term is small and both can be neglected for these case studies. Preliminary simulations were carried out both in 2D (SUPERFISH) for the input parameters (power densities) and in 3D (ANSYS Electromagnetic Suite and ANSYS 16) and permitted to determine the position of the cooling channel, the cooling water path arrangements and the water input temperatures for vane and tank.

As for frequency sensitivities is concerned, it results that the average value is equal to $\chi_{R0} = 3.3$ MHz/mm.

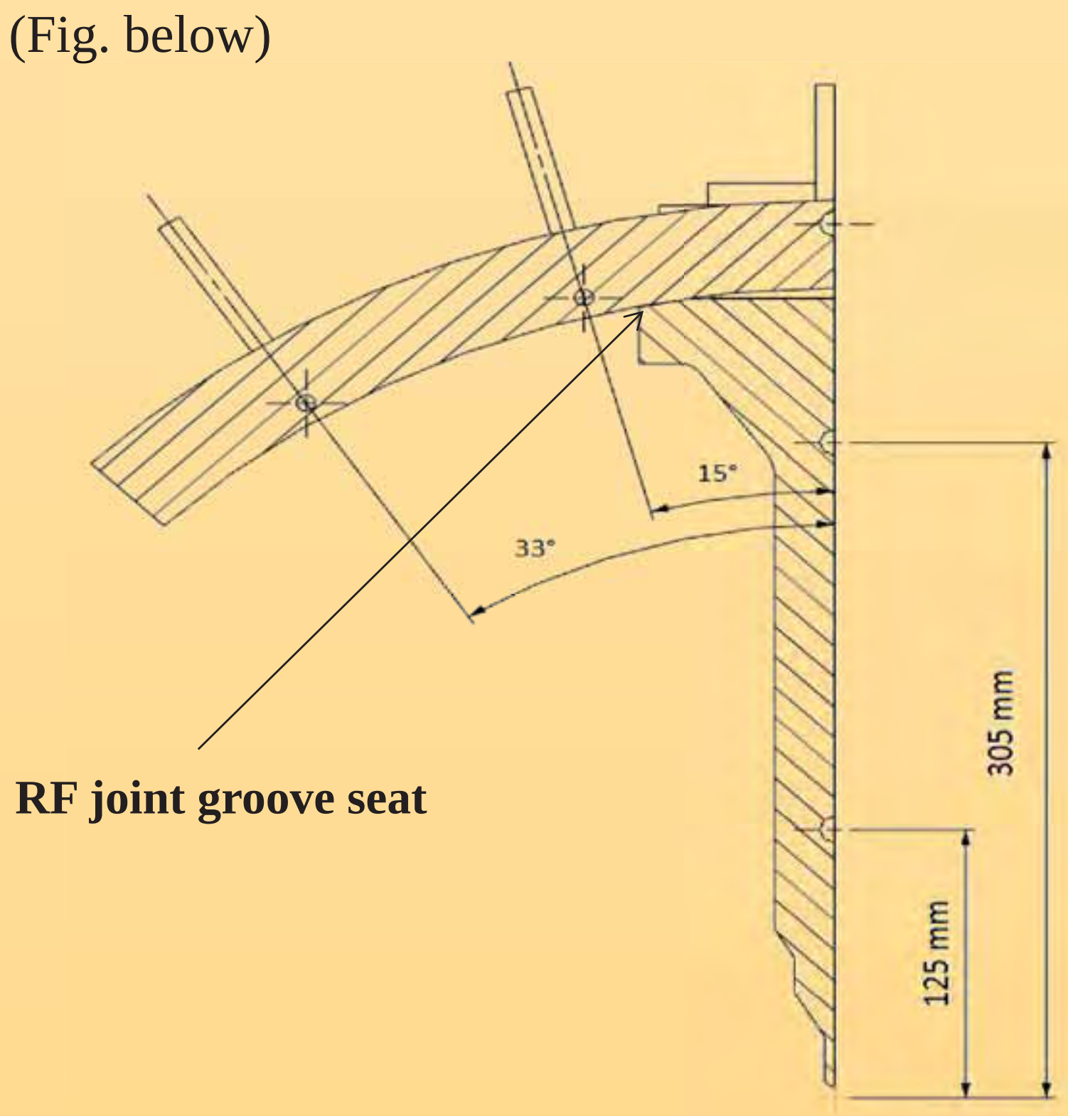
The outcomes of this analysis are the frequency sensitivities vs water temperatures and/or RF input powers in order to determine the actual tuning range with water temperature during RFQ operation.

COOLING SYSTEM

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 input water, 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 given cooling channel layout and inlet temperature, the associated temperature and displacement fields in the RFQ as well as the mechanical stresses.



It is important to notice two main aspects of this RFQ: first, the vane and the tank are thermally insulated (only a RF joint placed between the vane and the electrode ensures RF sealing) and second the RF power balance is approximately 60% on the vanes (Cu) and 40% on the tank (SS). The channel radii are R_{c2}=6 mm on the vane and R_{c1}=4 mm on the tank, the inlet water velocity is 3 m/s and consequently the heat convection coefficient h_c varies with temperature, which the mean stay at 11000 W/(m²·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. below)

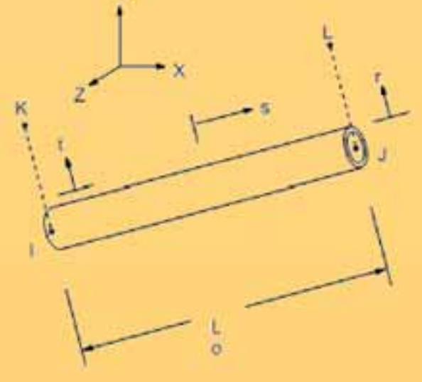


From the above figures, it is possible to notice that

- 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 brazed insert a cooling channel on the tank is foreseen with same radius inlet temperature of the vane ones.

FLUID116 DESCRIPTION

Simple thermal simulations often contain convective load in which heat transfer is dependent on difference between T_{surf} and a T_{bulk}, where T_{bulk} is a fixed unique bulk temperature of the fluid over the entire area considered. This assumption is acceptable if water does not change its temperature, as well as its properties across the cooling channel. In our case, tip displacement could be affected by temperature variation of solid body and hence the frequency response varies. For that reason a simulation with classical convection load was compared with another one that uses thermal fluid element in terms of tip displacement.



Fluid element was created using line bodies, so the model contains solid and line elements. Temperatures from surface of associated convection element areas are used, as well as convective heat transfer coefficient, to calculate bulk temperature variation of the fluid on the cooling channel path. Convection is considered between nodes I and K and between nodes J and L. Areas in which the convection occur must be selected from the named selection group. The line elements, specified as thermal fluid, have to be loaded with a mass flow rate and a temperature at inlet node. This element also make use of the well-known Bernoulli's equation to calculate pressure drop but here this study is not taken into account.

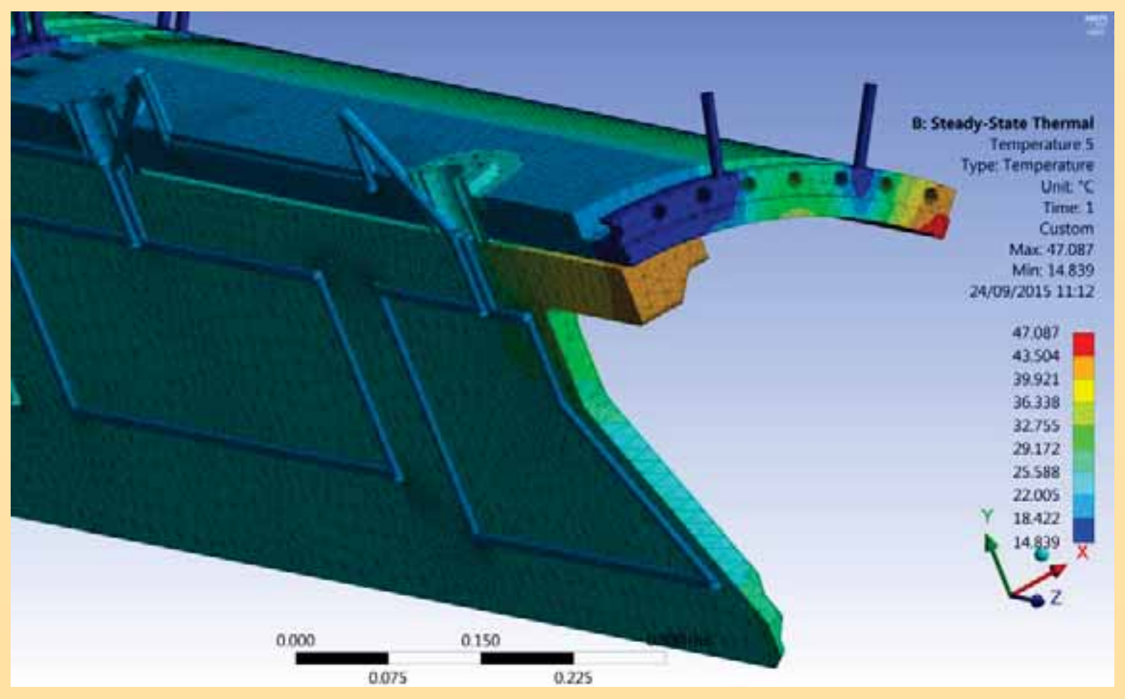
FLUID116 element allow the use of thermal convection loads without involving expensive CFD calculations. It is possible to vary the coefficient of convective heat transfer by imposing it through a table and allows both to quickly optimize the geometry and to adjust mass flow parameter to match results of experimental studies.

THERMO-STRUCTURAL MODEL AND RESULTS

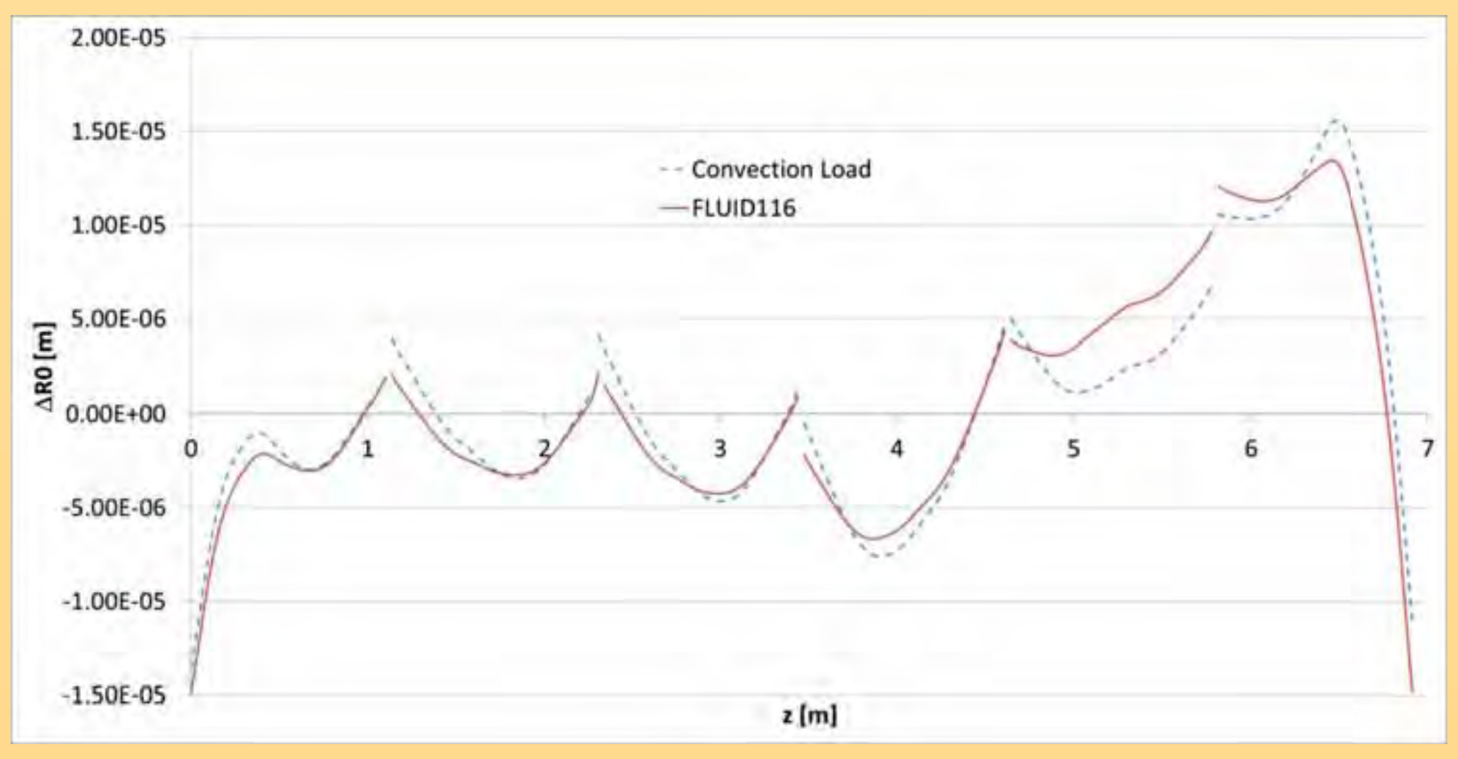
The 3D simulations were performed with the ANSYS Workbench v.16.2 software on 1/8 of the overall RFQ, including vane undercuts. The model is composed of steady-state thermal simulation coupled with a static structural. Symmetry plane conditions are used to the cutting planes. Thermal simulation contains 570'000 10-nodes tetrahedral elements, and 3000 thermal fluid element FLUID116, temperature variables are used for both element type. Another simulation was carried out without FLUID116 element but with simple convection load in which T_{bulk} are based on the average between inlet and outlet temperatures according to:

$$T_{out1[2]} = T_{in1[2]} + (1/\dot{m}c_p)\int_{z_{in}}^{z_{out}} p_{d1[2]}(z)dz$$

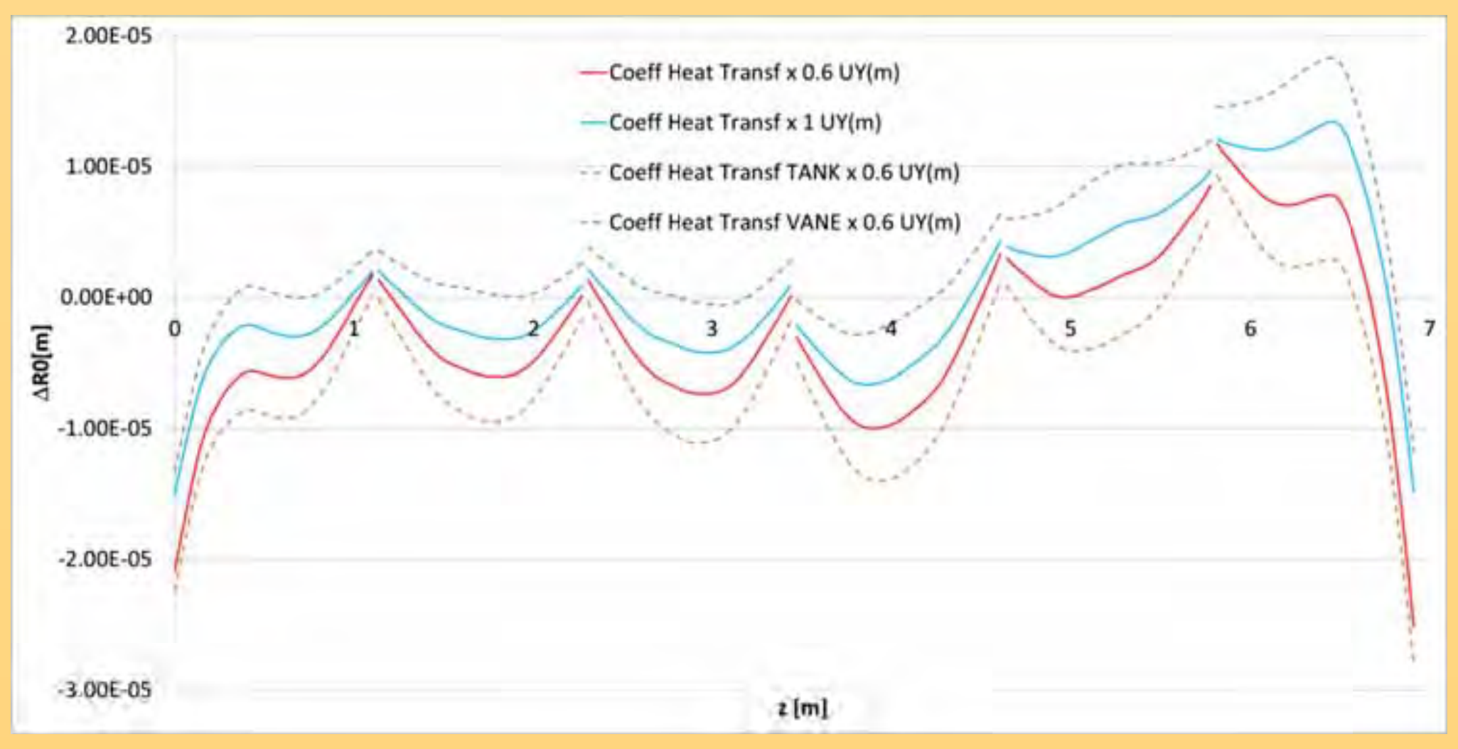
Where $p_{d1[2]}$ is the power density distribution [W/m²] on the vane [tank] extrapolated using SUPERFISH at each RFQ section. Accordingly to the Electromagnetic simulation results, heat fluxes varies along *z* and were applied to cavity surfaces via a table APDL command. Moreover, on the vane undercuts the power densities were calculated with ANSYS Electromagnetic Suite v 16.1 and then applied to each corresponding area as thermal heat flux. Inlet temperatures and mass flow rate are exposed on previous paragraph.



For what concern the static structural analysis , same solid elements were used with displacement variables. Body temperatures are introduced by thermal load. Secant thermal expansion coefficient of copper and stainless steel are introduced as well as Young modulus and Poisson coefficient. Remote points between adjacent tank were used to couple z displacements and to kinematic constrain the objects. In the following figure the ΔR0 (z) deformation is shown for the case T_1=15°C, T_2=20°C with the new element and the classical convection load..



Reductions of heat convection coefficient h_c of 40% are considered to evaluate its sensitivity respect to tip displacement on various cases



Variation of water inlet temperature both on vane and tank channels are used in order to evaluate the tip displacements and then evaluate the frequency sensitivity (not included).

CONCLUSIONS

The outcomes of the combined Electromagnetic and Thermo-Structural studies validate the current channel layout. The frequency temperature sensitivity was investigated. The vane temperature coefficient $\partial f/\partial T2$ 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. Electrode displacements in all hc conditions have only a little effects on the field distribution (0.5%, to be compared with 3% specifications)

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