

COMBINED ELECTROMAGNETIC-THERMAL-STRUCTURAL SIMULATION OF THE FOUR-METRE RADIO FREQUENCY QUADRUPOLE TO BE INSTALLED ON THE FRONT END TEST STAND

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Abstract

The front end test stand (FETS) [1] being constructed at the Rutherford Appleton Laboratory is entering the next stage of commissioning, with the three-solenoid magnetic low energy beam transport (LEBT) now installed and undergoing commissioning. The next major component to be manufactured is the 3 MeV, 324 MHz, four metre radio frequency quadrupole (RFQ). The mechanical design is almost complete so a comprehensive finite element model of the entire RFQ has been made in ANSYS to ensure the electromagnetic, thermal and structural properties are sound. An analysis of the cooling strategy and expected resonant frequency shift due to thermal expansion are presented.

INTRODUCTION

The FETS collaboration have chosen a four-vane design [2] for the RFQ needed to accelerate an H⁺ ion beam to 3 MeV with up to 95% transmission and with transverse normalised RMS emittances maintained at 0.25 π mm mrad. A frequency of 324 MHz was chosen due to the availability of a (now commissioned) Toshiba klystron and to be a good test of the novel ‘perfect chopping’ [3] technique to be demonstrated on FETS. The klystron will inject up to 2 MW of RF power at 10% duty factor into the RFQ. This puts large demands on the cooling strategy chosen, as the RFQ must be sufficiently cooled such that the cavity stays on tune and the beam dynamics aren't affected by thermal gradients in the vanes. This paper outlines the simulation work performed to predict the resonant frequency of the present RFQ design, the temperature rise at full RF power, the thermal expansion of the copper and the resulting frequency shift. The present cooling strategy will be evaluated and necessary improvements discussed.

PREPARING THE MODEL

The mechanical design [4] of the RFQ is being completed using Autodesk Inventor. The present design has the RFQ constructed from four one-metre sections; identical, except for the vane modulations. An IGES file of the CAD geometry was imported into ANSYS Workbench, where the Design Modeller module was used to prepare the geometry for simulations. This involved removing irrelevant features such as bolt holes and slicing by three symmetry planes, leaving one eighth of a one-metre section, or 1/32 of the entire RFQ. End walls were added to close the cavity before ‘filling’ it with a vacuum body suitable for performing a high-frequency eigenmode

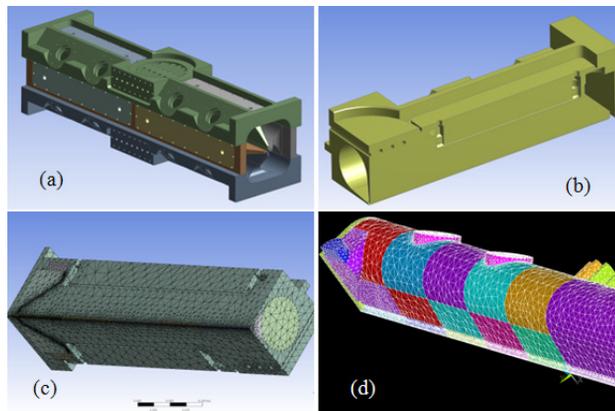


Figure 1: The imported IGES model of a 1m RFQ section (a) was simplified (b) before meshing (c). The mesh and boundary conditions were then transferred to ANSYS Classic (d) to calculate eigenmodes and EM fields.

analysis. The vacuum body, boundary and bulk copper were meshed in order to calculate the resonant frequency, wall heat flux and thermal/structural distributions, respectively. A graphical summary is shown in Fig. 1.

Having performed the CAD work and simulation setup in Workbench, an ‘ANSYS Input File’ was written so the mesh and boundary conditions of the sequential solvers could be read in by ANSYS Classic which is able to perform high-frequency eigenmode analyses.

RESONANT FREQUENCY

The dipole mode was calculated in the eigenmode solver but the results were not taken through to the thermal and structural solvers as the majority of the power is used by the quadrupole mode. The quadrupole and dipole mode frequencies were found to be 333.56 MHz and 330.02 MHz respectively. This result conflicts with simulations and experiments on the RFQ cold model [2, 5] which had the correct quadrupole frequency of 324 MHz and the dipole mode at a higher frequency. The difference was determined to be because of the geometry changes between the 40 cm cold model and the 100 cm real RFQ section. A revised mesh was created to test how the resonant frequencies varied with both total length and position of features such as RF couplers. The results are shown in Fig. 2. The quadrupole mode is at the design frequency when the RFQ has the length of the cold model, whilst asymptotically increasing to the 338 MHz predicted by a Poisson Superfish model of an infinitely long RFQ.

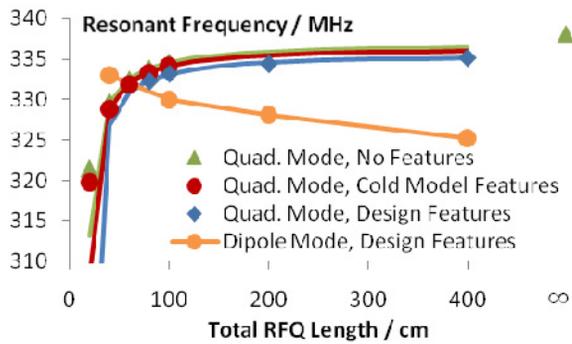


Figure 2: Variation of the quadrupole and dipole eigenmode frequencies with the total length of the RFQ and the position of features such as couplers and tuners.

The dipole and quadrupole modes cross over for an RFQ 50 cm long, before becoming well separated for the 4 m RFQ to be manufactured. In short cavities, the end wall significantly affects the total capacitance and hence resonant frequency. These end effects are minimal when the cavity becomes longer than about two metres. The RFQ will need the walls moved out by 4 mm to reduce the frequency to 324 MHz.

SURFACE HEAT FLUX

A macro [6] is used to calculate the surface currents caused by the magnetic fields and convert them into heat flux loads for the thermal solver. The total heat load over the surface is normalised to that expected in the full RFQ. For an intervane voltage of 85 kV (1.7 Kilpatrick), a peak power of 500 kW is needed for the 4 m RFQ. Allowing a large safety margin to account for localised heating, copper imperfections, beam loss and the need to vary the vane voltage about the optimum, a peak power of 800 kW is used in the thermal simulations. For a maximum 10% duty factor, the total heat load applied to the 1/32 model in Fig. 1 is thus 2500 W. Heat flux is applied to each mesh element on the vacuum-copper boundary, matching the magnetic field intensity distribution. Figure 3 shows a

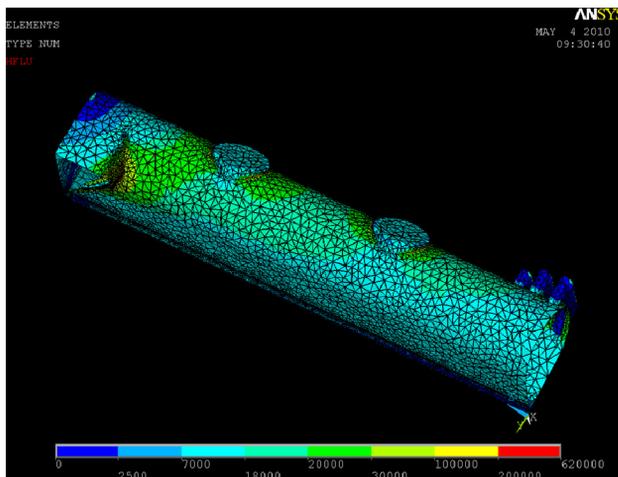


Figure 3: Wall heat flux distribution in units of Wm^{-2} .

peak heat flux of $62 Wcm^{-2}$ at the cut-back of the vane ends, and an average heat flux on the walls of approximately $1.5 Wcm^{-2}$. Accordingly, about 1500 W of heat is directly applied to the end of the vanes, 825 W to the curved walls and 175 W to the remaining features such as vacuum, coupler and tuner ports.

THERMAL SOLVER

With the heat flux distribution applied to the surface elements, the resulting copper temperature distribution was calculated with the ANSYS thermal solver. A heat transfer coefficient (HTC) of $20 Wm^{-2}K^{-1}$ was applied to the outer walls exposed to $22^{\circ}C$ stagnant air. The vacuum, tuner and coupler port cooling channels were estimated to achieve HTCs in excess of $3000 Wm^{-2}K^{-1}$. Unknown is what HTC the novel ‘cooling pockets’ [4] will have. It is hoped that with sufficiently large water flow rates and surface areas, the pockets should achieve HTCs of $3000 Wm^{-2}K^{-1}$. The water in all the coolant channels is at $15^{\circ}C$.

The resulting temperature distribution in the copper is shown in Fig. 4. The temperature distribution is quite uniform along the length of the RFQ. However the high heat flux at the vane cut-backs is not sufficiently removed by the cooling pockets so the vane tips become significantly hotter at $65^{\circ}C$ than the rest of the RFQ.

THERMAL EXPANSION

The FETS RFQ will not be tuned by precisely setting the water temperature in a network of cooling channels. Instead, the symmetrical design creates a homogenous thermal expansion, minimising the frequency shift. Fixed slug tuners will be used to ensure longitudinal field flatness; movable slugs will be used for active tuning.

The only parts of the RFQ that have a problematic thermal expansion are the vane tips where there is a temperature gradient of approximately $35^{\circ}C$ along a length of 10cm; one can estimate by hand a thermal expansion of approximately $60 \mu m$ at the vane tips.

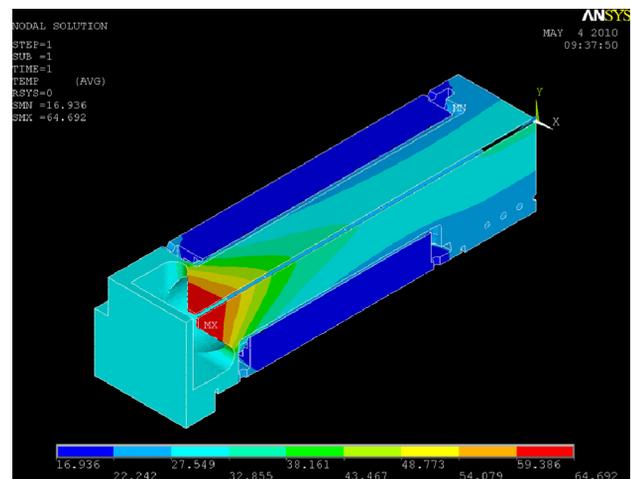


Figure 4: Copper temperature distribution in $1/8^{th}$ of a 1 m RFQ section with 2500 W input power (see text) and the predicted HTCs of the proposed coolant strategy. Colour scale is from $17^{\circ}C$ (blue) to $65^{\circ}C$ (red).

Transferring the temperature distribution to the ANSYS structural solver, the thermal displacements were calculated. The results are shown in Figs. 5 and 6. The end walls are free to expand longitudinally to relieve stresses that build up at the vane cut-backs. The vane tips have net longitudinal expansion of 62 μm which agrees well with the hand calculation but may be a problem for the RFQ matching section. Therefore, a squirt nozzle concept is being designed to actively cool the vane tips. The vanes have net transverse expansions 25 μm toward each other, which is just within machining tolerances.

FREQUENCY SHIFT

The displacements of the surface nodes and the EM fields inside the cavity were exported to Matlab where a macro was written to calculate the frequency shift of the RFQ using the Slater perturbation algorithm [7]. Fig. 7 shows a linear change in temperature and frequency shift

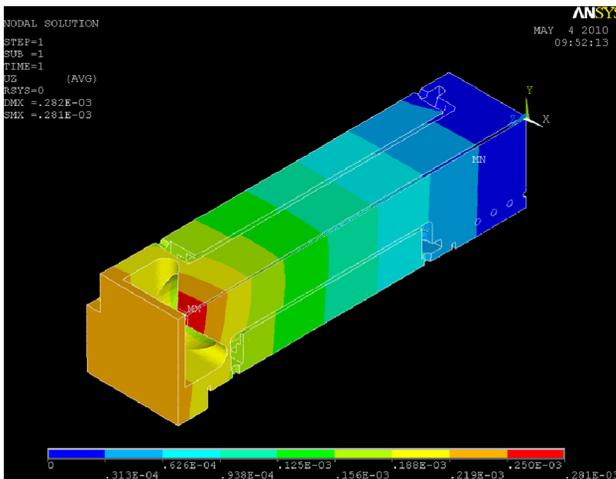


Figure 5: Longitudinal displacement. The end wall grows 219 μm (orange) and the vane tip 281 μm (red) giving a net vane tip expansion of 62 μm toward the end wall.

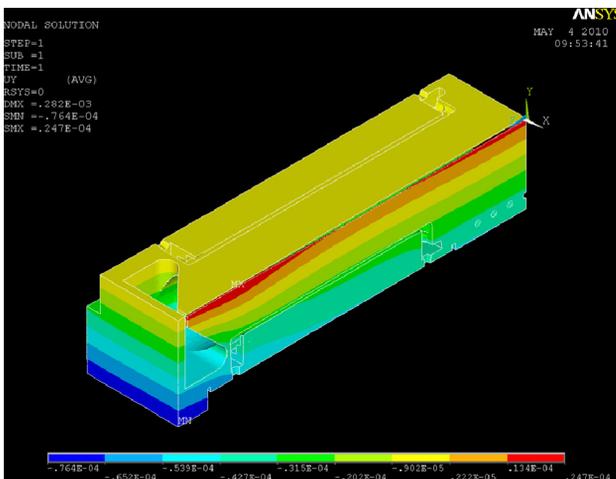


Figure 6: Vertical displacement (same horizontally). The outer walls expanding out 764 μm (blue) counteract the inward motion of the vanes, resulting in a net movement of the vanes 25 μm closer together (red).

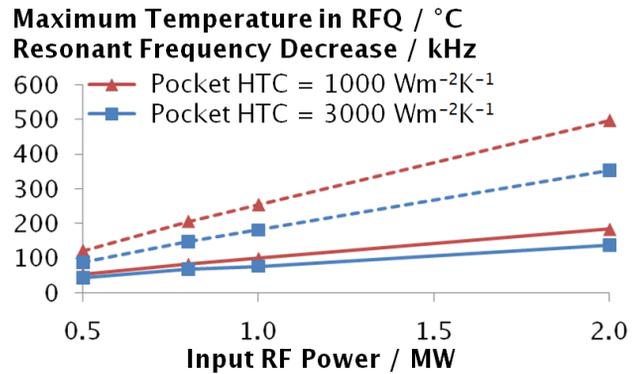


Figure 7: Variation of vane tip temperature (solid) and reduction in resonant frequency (dashed) with input RF power and heat transfer efficiency of the cooling pocket.

with input RF power. The frequency decreases by 149 kHz with 800 kW of RF power and cooling pocket HTCs of 3000 $\text{Wm}^{-2}\text{K}^{-1}$, which is well within the 10 MHz range of the movable slug tuners. The thermal and frequency shift calculations were benchmarked against the measurements made on the RFQ cold model, with the results summarised in Table 1.

Table 1: Comparison of Simulated to Measured Temperature Rise and Frequency Shift of the RFQ Cold Model with 60 W of DC Input RF Power and No Cooling

	Simulation	Measurement
Temperature rise	15 °C	15.6 °C
Frequency shift	-78 kHz	-89 kHz

CONCLUSIONS

The ANSYS simulations and Slater frequency perturbation calculations agree well with the values measured on the RFQ cold model, justifying the decision to progress simulations to the fully cooled 4 m RFQ. The expected frequency shift of ~150 kHz can be dealt with by the movable tuners and the small transverse expansion of the vanes should not affect field flatness or beam dynamics. The vane tips become significantly hotter than the rest of the RFQ and their longitudinal expansion is the primary cause of frequency shifts; therefore they should be directly cooled with squirt nozzles. A CFD simulation will be performed to better predict HTCs and test the squirt nozzle concept, but overall the novel ‘cooling pocket’ strategy is effective and will be taken forward.

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