RF, THERMAL, AND STRUCTURAL FINITE ELEMENT ANALYSIS OF THE PROJECT X INJECTOR EXPERIMENT (PXIE)* CW RADIO-FREQUENCY QUADRUPOLE (RFQ)

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ABSTRACT

PXIE (Project X Injector Experiment) is a prototype front end system for the proposed Project X accelerator complex at Fermilab [1]. An integral component of the front end is a 162.5 MHz normal conducting CW (continuous wave) radio-frequency quadrupole (RFQ) accelerator that has been designed and is being fabricated by LBNL. The RFQ will accelerate H^- ions from 30 keV to 2.1 MeV [2]. The four-vane RFQ consists of four modules with a total length of 4.45 meters. Through application of finite element analysis (FEA), the electromagnetic fields and their resultant effect on the RFQ body temperature and the subsequent deformations due to thermal expansion have been simulated. The analysis methodology developed at LBNL allows for quick evaluation of RFQ temperature, stress, deformation and the resulting effect on frequency without requiring the construction of a prototype. The technique has been applied to the following: RFQ body, RFQ cutbacks, fixed slug tuners, and pi-mode rods. The analysis indicates that the total heat load on the RFQ will be approximately 80 kW, which is removed via water-cooled passages.

INTRODUCTION

The PXIE RFQ is a front end injector for the proposed Project X experiment at FNAL. As this RFQ will operate in continuous-wave (CW) mode, the engineering design and analysis is critical for managing the thermal performance. The aim of this paper is to introduce that analysis method used to determine the heat loads experienced by the RFQ, how these loads affect operating temperature, and how temperature increase affects frequency and the methods by which the cooling water can be used to mitigate the RF heating effects on frequency.

RFQ BODY SIMULATION

The body of the RFQ is simulated using a thin 3D slice of the RFQ cross section. Only one-quarter of the geometry is simulated due to symmetry. The first step of this step in the simulation is to create a vacuum geometry that corresponds to the solid RFQ body. Once created, ANSYS Multiphysics [4] performs RF analysis on the vacuum geometry. Once complete, the RF heat load is calculated and applied to the inner cavity walls of the RFQ body model. Convective water cooling is applied to the gun-drilled cooling channels, as shown in Fig. 1.

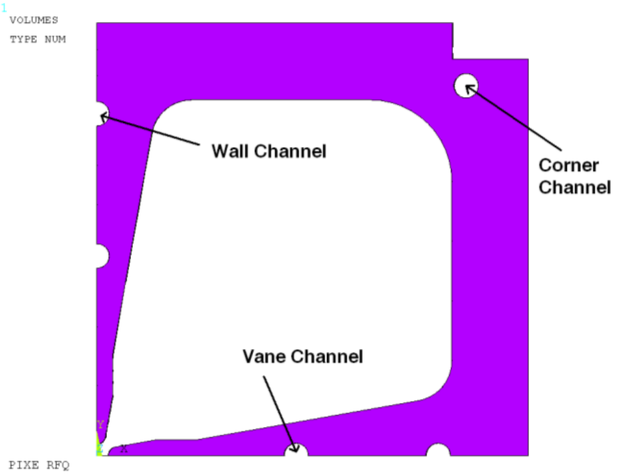

Figure 1: RFQ body cross section with gun-drilled cooling channels.

Assuming that the cooling water is at 30 °C, the resulting temperature profile at steady-state operation is shown in Fig. 2.

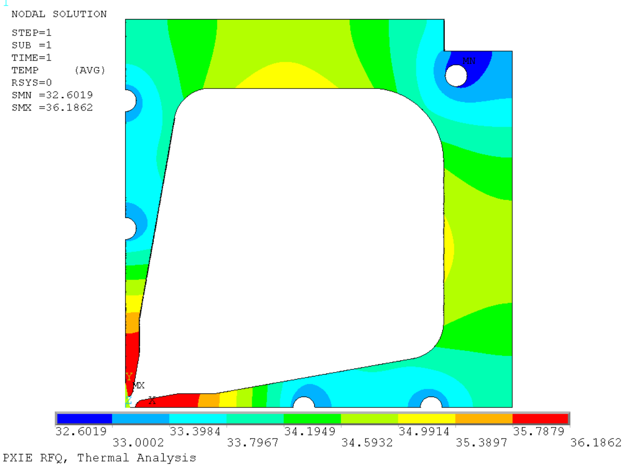

Figure 2: Temperature contours (°C) for steady-state RFQ operation.

The maximum temperature is 36.2 °C and is located at the vanetips. Minimum temperature is approximately 32.6 °C, and is found in the corner cooling passage. Overall, it is evident that with the current cooling scheme, the RFQ body temperature only rises 2.0 – 6.0 °C above nominal water temperature. This temperature rise causes expansion of the cavity walls away from the beam axis, and growth of the vanetips towards the beam axis. Both of these affect the resonant frequency of the cavity. The thermal results are piped into a structural analysis which determines the displacements due to thermal expansion, the results of which are shown in Fig. 3.

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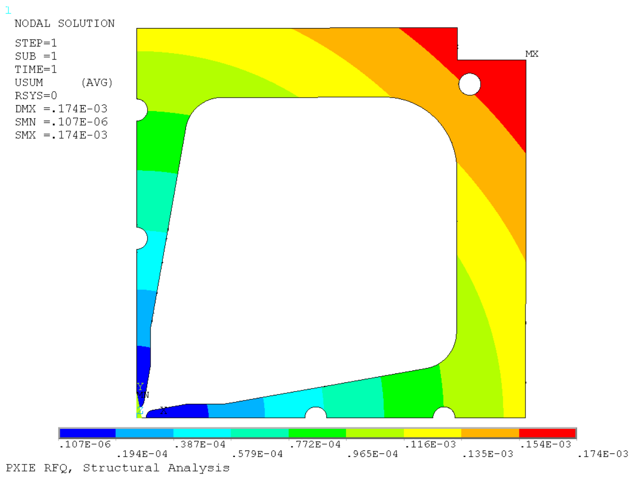

Figure 3: Thermal displacement (m) due to RF heating.

As surface nodes are shared between the vacuum and solid body meshes, the displacements are used to morph the vacuum mesh such that it reflects the deformed geometry. This new cavity geometry, which represents the steady-state operating condition, is used for a final RF analysis to determine the frequency shift due to RF heating and subsequent steady-state frequency. The uncorrected ideal, nominal and steady-state frequencies are shown in Table 1.

Table 1: RFQ Frequencies

Condition	**Frequency (MHz)**
Ideal	164.36
Nominal	164.28
Steady State	164.27

As Table 1 shows, the frequency drop from initial start up, i.e. nominal frequency, to the final steady state frequency is approximately 10 kHz. This drop is due to RF heating, with thermal equilibrium achieved roughly 10 minutes after RF power turn on. Varying the cooling water temperature in the vanes and walls provides some differential dynamic tuning capabilities that mitigate the frequency shift due to RF heating. The frequency sensitivity to cooling water temperature change is shown in Table 2.

Table 2: Frequency Shift Due to Cooling Water Temperature Change

PXIE Frequency Shift	**Average Result**
Overall (kHz/°C)	-2.8
Vane (kHz/°C)	-16.7
Wall (kHz/°C)	13.9
Theoretical Shift (kHz/°C)	-2.9

As the table shows, the theoretical shift closely matches the simulated overall shift, evidencing the accuracy of the FEA model.

RFQ BODY SIMULATION

The RFQ cutbacks are simulated in a similar fashion as the thin slice model. A sub-model of the cutbacks was created and RF analysis in ANSYS was carried out. The result is piped into a thermal simulation, the outcome of which is shown in Fig. 4.

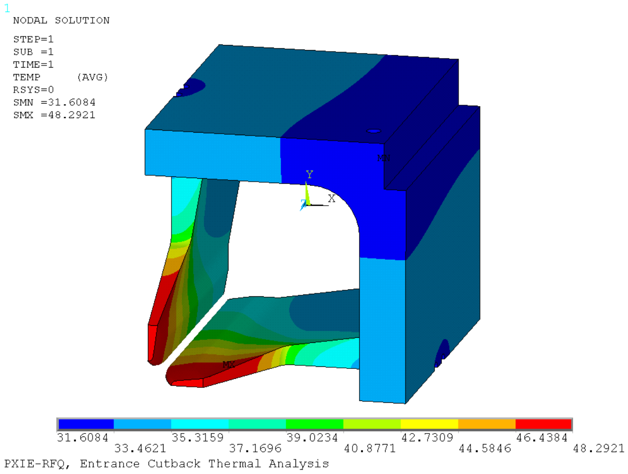

Figure 4: RFQ cutback temperatures (°C) at entrance.

As Fig. 4 shows, the maximum temperature occurs at the tips of the cutbacks, which is the location is the farthest from the cooling channels.

PI-MODE RODS

ANSYS Workbench is used to simulate the heating in the pi-mode rods, which are made from OFHC copper. The pi-rods are brazed into the RFQ structure and cooled via water that is pumped through their inner bore. Heat loads are approximated from ANSYS Multiphysics and CST Microwave Studio. The temperature results are shown in Fig. 5.

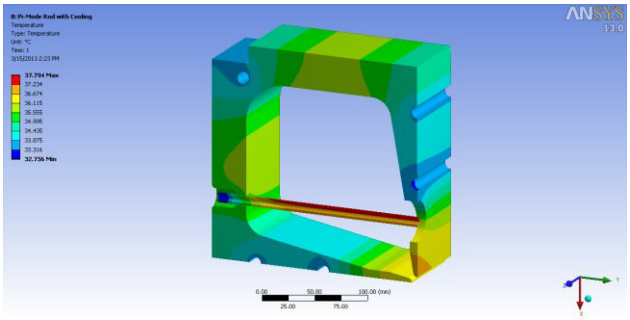

Figure 5: RFQ body and pi-mode rod temperatures (°C).

As Fig. 5 shows, assuming a nominal cooling water temperature of 30.0 °C, the resulting maximum rod temperature is 37.8 °C. As long as cooling water is flowing, the pi-rod temperature is effectively managed. However, in the event of a cooling water failure, failsafe systems will shut down RF power; this is to avoid

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excessive heating of the pi-rods, which could cause material yielding due to thermal expansion.

RFQ FIXED SLUG TUNERS

The slug tuners are made from OFHC copper and are installed in their respective ports using a snap ring. An RF spring mitigates any RF leakage at the mating surfaces, and an O-ring is used to seal the vacuum. The slug tuners do not have any active cooling, but instead rely on conductive heat transfer to the RFQ body.

The heat load on a given slug tuner is a function of its penetration depth into the RF cavity; nominal intrusion is 20.0 mm, while min and max intrusion is +/- 20.0 mm from nominal, which gives a tuning bandwidth of +/- 1.4 MHz. The worst-case heating situation corresponds to a slug tuner at maximum intrusion of 40.0 mm, located at the cutbacks. Evaluation of this situation yields a conservative estimate of the conductive cooling capability of the slug tuner to RFQ body interface. The heat flux into a slug tuner for the described condition is shown in Fig. 6.

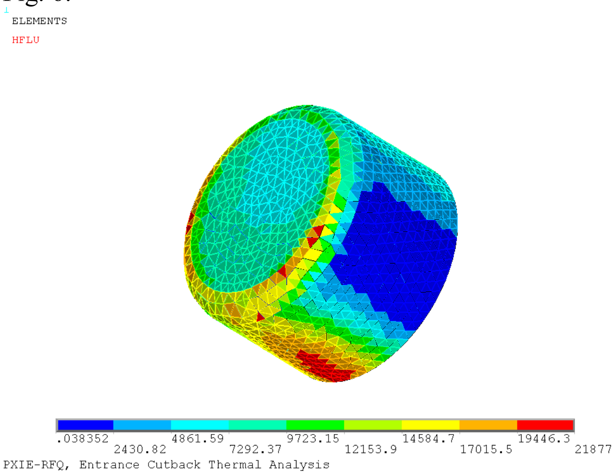

Figure 6: Slug tuner heat flux (W/m^2) at 40.0 mm intrusion.

The heat flux is integrated over the area of the slug tuner to provide the total heat flow into the tuner, which is ~80 W. This heat flow is then used in ANSYS workbench to simulate heat transfer from the slug tuner to the RFQ body. To mimic the effect of contact resistance, the effective area for conductive heat transfer is reduced to less than 10% of its actual area. The resulting temperature profiles are shown in Fig. 7.

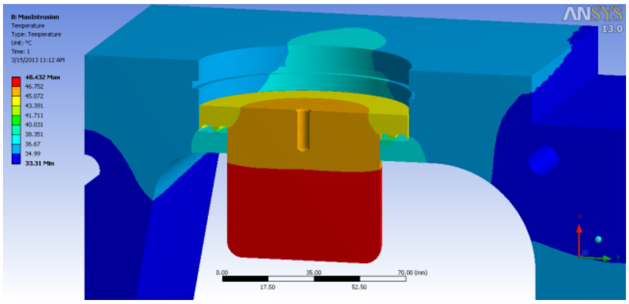

Figure 7: Slug tuner temperatures profiles (°C)

The maximum tuner temperature is 48.4 °C, which is not problematic. It is unlikely that any of the slug tuners will experience this worst-case scenario; however, in the event that this situation does occur, the conductive heat transfer to the RFQ body is sufficient to cool the slug tuners.

TOTAL RFQ HEAT LOAD

From this analyses, it is possible to calculate the total RFQ heat load, and hence the required cooling that must be supplied to maintain stable operating temperatures. The total heat load of each module is tabulated in Table 3, with the overall total heat load summed at the bottom.

Table 3: Module Heat Loads Due to RF

Component	Heat Load (kW)
Module 1	19.2
Module 2	19.7
Module 3	19.7
Module 4	19.4
Total	**78.0**

As Table 3 shows, the total RFQ heat load is approximately 78.0 kW. This includes the heat of the RFQ body, cutbacks, pi-rods and slug tuners. Assuming a 30% contingency factor, the required cooling system should have a cooling capacity of ~100 kW.

CONCLUSION

This paper illustrates how the use of FEA provides successful prediction of RFQ operating parameters, as well as providing information that helps to size external systems without requiring a prototype module or rigorous experimental testing.

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