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DESIGN AND ANALYSIS OF THE PXIE CW RADIO-FREQUENCY QUADRUPOLE (RFQ)*

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Abstract

The Project X Injector Experiment (PXIE) will be a prototype front end of the Project X accelerator proposed by Fermilab [1]. PXIE will consist of an H^- ion source, a low-energy beam transport (LEBT), a radio-frequency quadrupole (RFQ) accelerator, a medium-energy beam transport (MEBT) and a section of superconducting cryomodules that will accelerate the beam from 30 keV to 30 MeV [2]. LBNL has developed an RFQ design for PXIE with fabrication scheduled to begin before the end of CY 2012. The chosen baseline design is a four-vane, 4.45 m long CW RFQ with a resonant frequency at 162.5 MHz (2.4 wavelengths long). The RFQ will provide bunching and acceleration of a nominal 5 mA H^- beam to 2.1 MeV. The relatively low wall power density results in wall power losses that are less than 100 kW. The beam dynamics design has been optimized to allow for more than 99% beam capture with exceptionally low longitudinal emittance. The RFQ mechanical design and a summary of various analyses are presented here.

INTRODUCTION

The PXIE RFQ design is a 162.5 MHz, 4.45 m long, four-vane structure consisting of four separate modules that will accelerate a 5 mA H^- beam to 2.1 MeV using a 60 kV vane-to-vane voltage. Most of the RF input power is dissipated on the cavity walls to establish the needed RF field with only about 12% of the total power transferred to the beam. Each of the approximately 1.1 m long RFQ modules will consist of four solid OFHC copper vanes that are modulated prior to being brazed together. A brazed copper structure has been chosen due to the high power, CW operation. A series of 32 water-cooled pi-mode rods provides quadrupole mode stabilization, and a set of 80 evenly spaced fixed slug tuners is used for final frequency adjustment and local field perturbation correction.

The PXIE RFQ design incorporates selected portions of the technology validated by the Spallation Neutron Source (SNS) Front End RFQ [3] designed and constructed at LBNL. By combining specific proven fabrication and assembly methods with the use of other appropriate high reliability, low cost features, LBNL has developed a design that poses low risk and is easily manufactured using readily available machinery.

Images from a 3-D CAD model of the completed RFQ design are used in this paper to present detailed descriptions of various design characteristics. An overall view of the full four-module RFQ is shown in Fig. 1.

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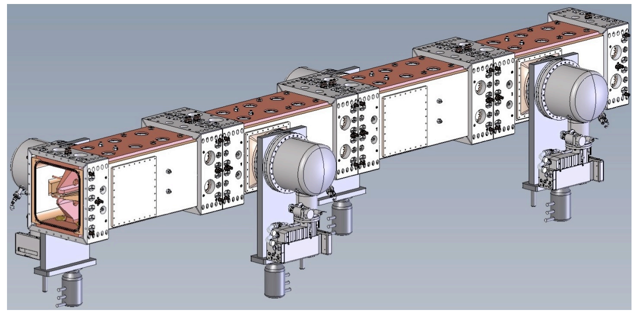

Figure 1: CAD model of the full four-module RFQ.

RFQ DESIGN DETAILS

Cavity Body

Each of the four vanes in a module are to be machined from a single piece of copper and will include simple cooling channels produced using an established gun boring technique. The RFQ vane tips are to be modulated by means of a fly cutter technique previously developed at LBNL using a commonly available programmable mill. Fiducial surfaces that also act as mating surfaces will be machined directly onto the vanes to provide high precision during both machining and assembly. Two vane geometries will be used (horizontal and vertical) with the opposing vanes being identical. Other features such as tuner ports, RF coupling ports, vane cut backs, cooling passage taps, vacuum pumping ports, pi-mode rod penetrations, sensing loop ports and tapped holes for the stainless steel joint plates are to be machined prior to finish machining of the cavity surfaces and vane tips. An exploded view of a single four-vane module and a cross section view of the RFQ body showing the cooling passage locations are provided in Fig. 2.

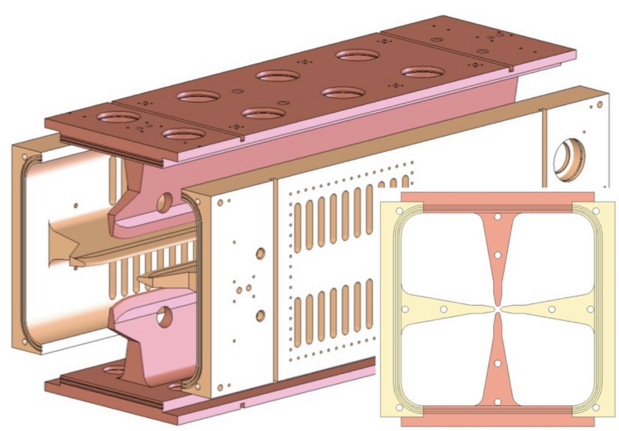

Figure 2: Exploded 4-vane module; RFQ cross-section.

The finished vanes are to be brazed together along axially running joints. A zero-thickness brazing process will be used in order to maintain the tight vane tip-to-vane tip tolerance, which is dictated by the high dependence of cavity frequency on vane tip spacing. Wire braze alloy will be loaded into grooves in the joint surfaces such that the alloy spreads throughout the joint during the braze cycle by means of capillary action. This technique permits the RFQ modules to be assembled and the cavity frequency measured prior to the braze cycle to allow for dimensional adjustments, if necessary.

A series of stainless steel plates are to be bolted to the outer RFQ surfaces at the ends of each module. These plates contain embedded bolt pockets to allow joining of the modules. No special alignment fixtures or procedures will be required to join the RFQ modules together as the ends are designed to be self-aligning by means of embedded dowel pins. The bolted end connections are sufficiently strong and stiff such that the fully assembled RFQ can be lifted and handled as a single unit. This characteristic also allows the RFQ body to be supported using a simple kinematic (or 6-strut) system that will not impart any direct bending stresses on the assembled RFQ. The joint plate concept is shown in Fig. 3.

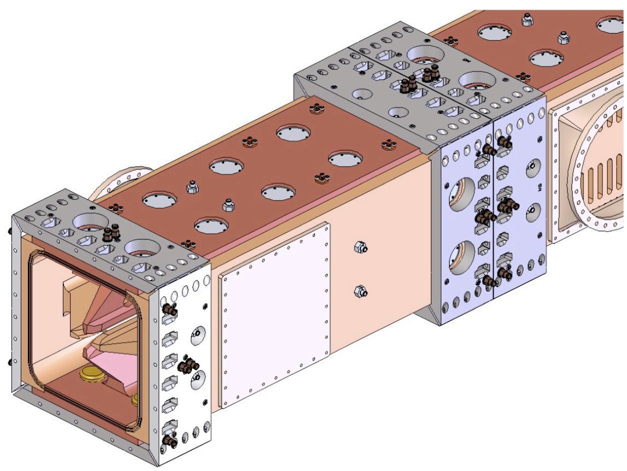

Figure 3: RFQ modules connected by joint plate method.

Cooling

A set of 8 cooling passages in the RFQ cavity walls are to be fed and controlled separately from the 4 channels embedded in the vanes. During operation, a combination of RF power dissipated in the cavity walls and heat removal through the cooling passages will cause the cavity to distort and shift in frequency. Continuous differential control of the cavity vane and wall water temperatures provides a fine-tuning of the structure frequency during operation. Since the cavity frequency is very dependent on vane tip spacing, separate temperature control of the vane water provides up to six times the frequency range of a single control circuit.

The passages are to be gun drilled from one end of the vanes with plug welds at the end penetrations. Each of the 12 mm diameter passages will carry approximately 16 liters per minute of cooling water. At the beginning of the first module and at the end of the fourth module, there will be vane cutbacks for proper termination of the RF cavity. The vane cooling passages will run close to the root of the cutbacks in order to accommodate the high local heat loads at the ends. A section view of a Module 1 horizontal vane is provided in Fig. 4 showing the geometry of the central cooling passages.

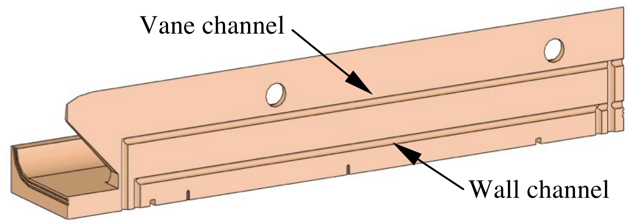

Figure 4: Section view of Module 1 horizontal vane.

Cavity Tuning

Cavity tuning will be achieved with fixed slug tuners distributed along the length of the modules. The design uses 20 tuners per RFQ module (1 per quadrant at 5 evenly distributed locations). Based on bead pull field measurements of the assembled RFQ, each set of four tuners at a given axial location will be custom machined to predetermined lengths. Primary RF sealing will be accomplished by a step in the tuner flange surface that interfaces with the RFQ wall. Behind the step, an RF coil spring will protect the O-ring, also located on the tuner flange. Load plates using setscrews will be held in place by a snap rings recessed in the copper vane wall and will provide the necessary sealing load. The tuners are to be machined from solid slugs of copper. CAD images of the tuner design are provided in Fig. 5.

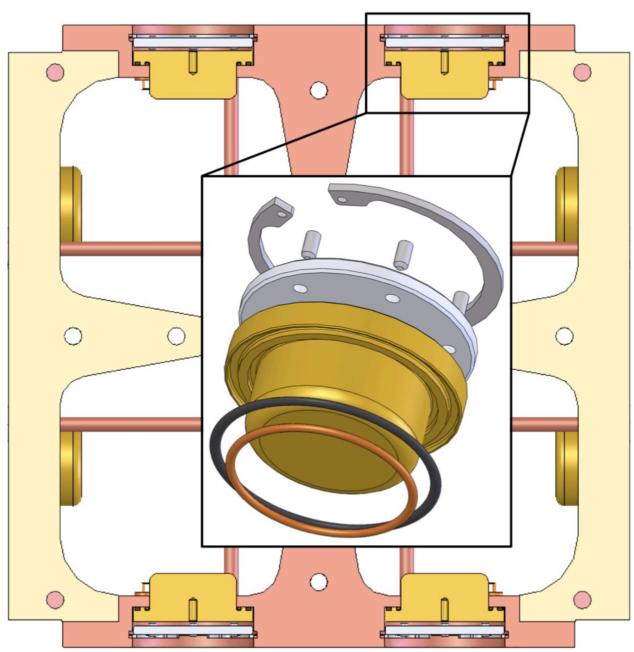

Figure 5: Fixed slug tuner details.

Pi-mode Rods

A series of Pi-mode stabilizer rods (4 pairs per module) will be incorporated to provide RF mode stabilization (to minimize the dipole mode and maximize the quadrupole mode). The rods will pass through the vanes and provide a direct connection between opposing cavity walls. The rods will be brazed into the cavity walls at the same time that the four vanes are brazed together. The rods will be 10 mm diameter hollow copper tubes with active water-cooling. Details of the rod geometry are shown in Fig. 6.

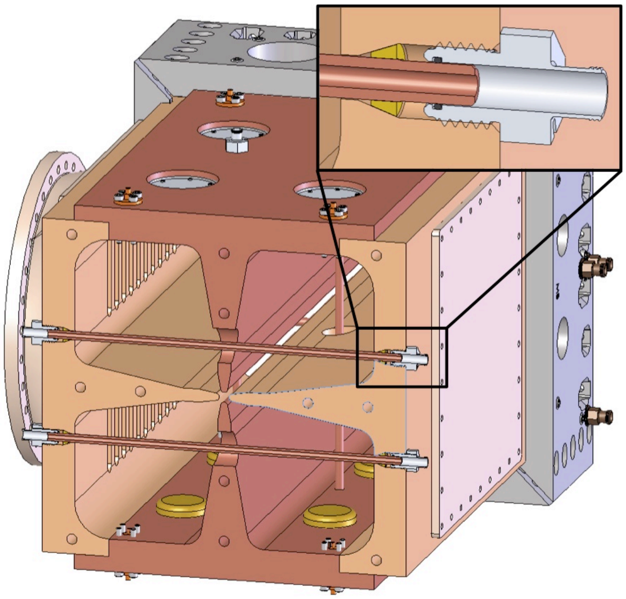

Figure 6: Pi-mode rod details.

Module RF and Vacuum Seals

The primary module-to-module RF connection will consist of a 3 mm wide, 250 μm high raised surface machined into the module ends around the periphery of the cavity. This sealing surface is to be backed up by a canted coil spring, which will absorb any RF that leaks past the primary seal. Outside of the canted spring is an O-ring, which provides the vacuum seal. The modules are bolted together at these joints as previously described.

THERMAL ANALYSIS

A series of RF and thermal finite-element models of the RFQ have been developed using ANSYS®[4]. The primary model consists of a one quadrant, 1 mm thick 3-D slice of the RFQ cross section. The thermal loads and constraints applied to the model include cavity wall heat flux from the RF, convective heat transfer on the cooling passage surfaces and symmetry boundary conditions.

From the RF analysis, the average linear power density was determined to be 137 W/cm with a peak heat flux on the cavity wall of only 0.7 W/cm^2. With 20°C water in both the vane and wall cooling passages, the resulting temperature profile in the cavity body ranges between 22 and 25°C at full RF gradient.

Additional modeling that has been carried out includes stress and displacement analyses, thermal analyses of the tuners, pi-mode rods and vane cutbacks, and prediction of the frequency shift of the RFQ cavity due to thermal loading and changes in the cooling water temperature. Examples of the temperature contour plots for the cavity body and vane cutback region (inset) are shown in Fig. 7.

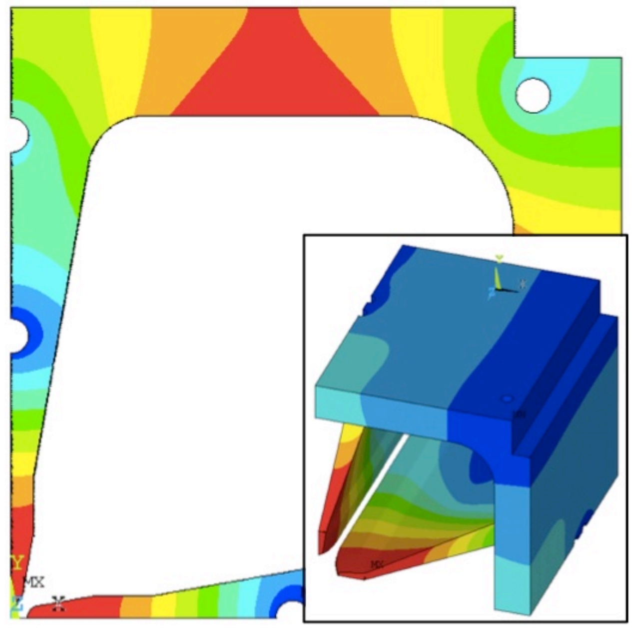

Figure 7: Temperature distribution in one RFQ quadrant.

The RFQ cooling scheme will use differential water temperature control in the vane and wall passages. This technique provides active tuning of the RFQ by holding the wall water temperature constant and adjusting the vane water temperature up and down. The frequency of the RFQ can be shifted by -16.7 kHz for every 1°C rise in the vane cooling water temperature. For uniform water temperature control, the shift would only be -2.8 kHz/°C.

SUMMARY

LBNL has developed a design for the Project X front-end RFQ. The design features and some of the associated thermal analyses were presented in this paper. The RFQ will incorporate selected technology validated by LBNL's development of the SNS RFQ. After a series of key fabrication tests are completed, construction of the actual RFQ modules will begin later this year.

REFERENCES

[1] S. Nagaitsev, et al, "Project X – A New Multi-megawatt Proton Source at Fermilab," PAC '11, New York, NY, USA, pp. 2566-2569.

[2] S. Nagaitsev, et al, "PXIE: Project X Injector Experiment," THPPP058, these proceedings.

[3] A. Ratti, et al, "The Design of a High Current, High Duty Factor RFQ for the SNS," EPAC '00, Vienna, Austria, pp. 495-497.

[4] ANSYS, Inc. (http://www.ansys.com).