FINAL DESIGN OF A CW RADIO-FREQUENCY QUADRUPOLE (RFQ) FOR THE PROJECT X INJECTOR EXPERIMENT (PXIE)*

S. P. Virostek#, A. J. DeMello, M. D. Hoff, A. R. Lambert, D. Li, and J. W. Staples
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

The Project X Injector Experiment (PXIE) now under construction at Fermilab is a prototype front end of the proposed Project X accelerator [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 [2]. The PXIE system will accelerate the beam from 30 keV to 30 MeV. The four-vane, brazed, solid copper design is a 4.45 m long CW RF accelerator with a resonant frequency of 162.5 MHz. The RFQ will provide bunching and acceleration of a nominal 5 mA H^- beam to an energy of 2.1 MeV. The average power density on the RFQ cavity walls is <0.7 W/cm^2 such that the total wall power losses are ~80 kW. LBNL has completed the final design of the PXIE RFQ, and fabrication is now under way. The completed PXIE RFQ will be assembled at LBNL and tested with low-level RF prior to shipping to Fermilab. Several aspects of the final RFQ mechanical design along with associated fabrication techniques are presented in this paper.

INTRODUCTION

The PXIE RFQ will operate at a 162.5 MHz resonant frequency and will accelerate a 5 mA H^- beam to 2.1 MeV using a 60 kV vane-to-vane voltage. The 4.45 m long, four-vane CW structure will be comprised of four approximately 1.1 m long longitudinal modules. Only about 12% of the total RF input power goes to beam loading with the rest dissipated on the cavity walls to generate the necessary RF field. The modules will consist of four solid OFHC copper sections that are fully machined with the vane tips modulated prior to being brazed together. Due to the high power CW operation of the PXIE RFQ, a brazed copper structure design has been developed. Final frequency adjustment and local field perturbation correction is accomplished by means of 80 evenly spaced fixed slug tuners. Quadrupole mode stabilization is achieved through a set of 32 water-cooled pi-mode rods. The overall approach for the PXIE RFQ was to combine specific proven fabrication and assembly techniques with other high reliability, low cost features in order to develop 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. A realistic CAD rendering of the full four-module RFQ is shown in Fig. 1 (rendering by Don Mitchell of Fermilab).

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spvirostek@lbl.gov

Figure 1: CAD model of the assembled RFQ.

RFQ DESIGN DETAILS

Cavity Body

Each module consists of four vanes that are to be machined from a single piece of OFHC copper and will incorporate simple cooling channels produced using a readily available gun drilling technique. Modulations will be machined on the RFQ vane tips with a custom designed fly cutter used in a computer controlled horizontal mill. In order to provide high precision during both machining and assembly, the mating surfaces where the vanes join together also serve as fiducial surfaces. Two different vane geometries will be used in each module (horizontal and vertical) with the opposing vanes being identical. Features located on the outer surface of the vanes such as tuner ports, RF coupling ports, cooling taps, vacuum pumping ports, pi-mode rod penetrations, sensing loop ports and tapped holes for the stainless steel module joining plates will be machined prior to finish machining of the inner cavity surfaces and vane tips. All of the vacuum and RF sealing surfaces for the cavity penetrations are recessed into the outer surface of the RFQ copper body to prevent damage during handling.

The modules will be formed by brazing together the finished vanes along the axially running joints. In order to maintain the tight vane tip-to-vane tip tolerances and ensure that the required field flatness and cavity resonant frequency can be achieved using the slug tuners, a zero-thickness brazing process will be used. Wire braze alloy will be loaded into grooves that are recessed into the joint surfaces. A series of specially designed clamps will hold the vane joints tightly together during the hydrogen oven braze. The alloy spreads throughout the close fitting joint during the braze cycle by means of capillary action. This

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technique permits the RFQ modules to be assembled and the cavity frequency and fields measured prior to the braze cycle to allow for dimensional adjustments, if necessary. The braze alloy to be used is Cusil, a copper-silver eutectic that has very low viscosity when liquid. An exploded view showing the four vanes of a single RFQ module is provided in Fig. 2.

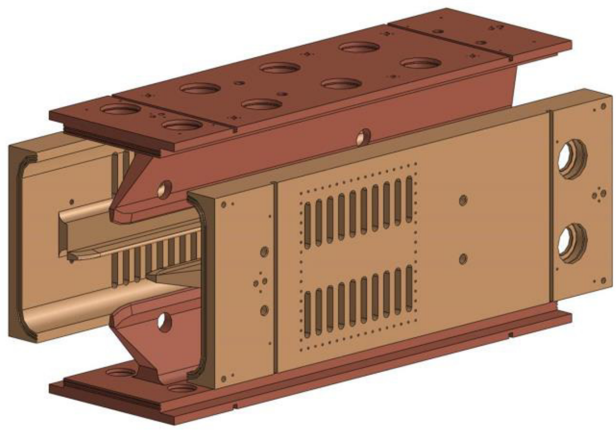

Figure 2: Exploded CAD view of a single module.

The final RFQ cavity is a four vane structure with four identically sized quadrants. A cross sectional view of the RFQ body showing the cavity geometry with cooling passages, tuners and pi-mode rods is shown in Fig. 3. Details of the RFQ features are discussed in the following sections.

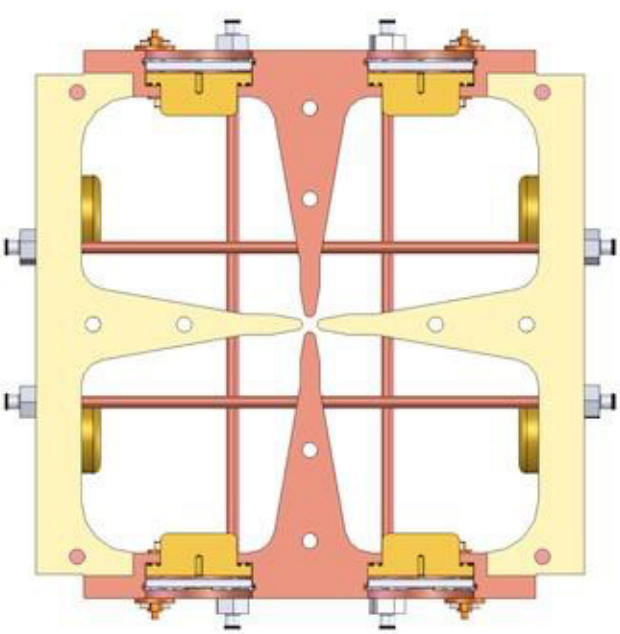

Figure 3: CAD model cross sectional view of the RFQ.

Cavity Cooling

The four cooling channels located in the RFQ vane tips will be supplied and temperature controlled separately from the eight cooling passages in the RFQ cavity walls. During operation, the combined effect of RF generated heat flux on the cavity walls and heat removal through the cooling passages will cause cavity distortion and a shift in the resonant frequency. By holding the wall cooling water constant and adjusting the vane tip water temperature, the structure frequency can be fine-tuned during operation. Due to the fact that the cavity frequency is very sensitive to the vane tip spacing, separate temperature control of the vane tip water provides approximately six times the frequency tuning range of a single cooling circuit.

The passages will be blind gun drilled into the vanes with e-beam plug welds at the end penetrations. Each of the 12 mm diameter passages will carry approximately 4 gallons per minute of cooling water. Vane cutbacks for proper termination of the RF cavity are located at the beginning of the first module and at the end of the fourth module. The cross drilled connection to the vane cooling passages will pass close to the root of the cutbacks to accommodate the higher local heat loads at the ends.

Cavity Tuning

Fixed slug tuners distributed along the length of the RFQ modules will provide cavity tuning. The final design uses 20 tuners per RFQ module (one per quadrant at five approximately evenly spaced locations). The tuners will be machined from solid slugs of OFHC copper.

The lengths of the tuners will be based on automated bead pull field measurements of the fully assembled RFQ modules. Each set of four tuners at a given axial location will be custom machined to the appropriate lengths. RF sealing of the tuners will be accomplished with a canted coil spring that will fit in a groove and be pressed against a recessed lip in the cavity wall. An O-ring outside the RF spring will provide vacuum sealing. A load plate using set screws will be held in place by a snap ring recessed in the RFQ wall and will provide the necessary sealing load on the tuner. The tuner components are shown in Fig. 4.

Figure 4: Fixed slug tuner components.

Pi-mode Rods

In order to minimize the dipole mode and maximize the quadrupole mode, four pairs of pi-mode stabilizer rods per module will be used to provide RF mode stabilization. The rods pass through holes in the vanes and provide a direct connection between opposing cavity walls. The pi-mode rods will be brazed into the cavity walls at the same time that the four vanes are brazed together. The rods are 10 mm diameter hollow OFHC copper tubes that are water-cooled.

RF and Vacuum Seals

A 3 mm wide, 250 μm high raised surface will be machined into the module ends around the periphery of the cavity to provide a primary RF connection between modules. The primary sealing surface will be backed up by a canted coil spring to absorb any RF that leaks past the initial seal. An O-ring outside of the canted spring will provide the vacuum seal. The modules will be joined together using a 'flangeless' joint design in which connecting bolts and nuts are recessed into stainless steel joint plates. The joint plates are connected to the RFQ body by means of a series of bolts and are keyed to a lateral groove in the RFQ outer wall to provide resistance to the axial forces. Fig. 5 shows a CAD view of the module-to-module joint configuration

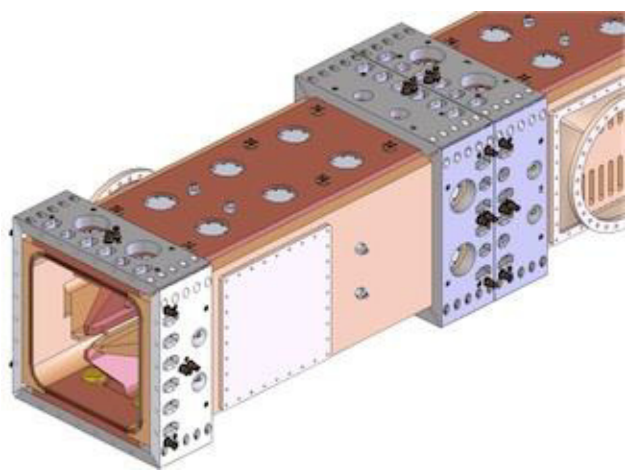

Figure 5: CAD showing a module-to-module joint.

Both RF and vacuum sealing are also required at the numerous penetrations into the RFQ cavities. The RF feed and sensing pick-up ports have sealing schemes that are similar to that previously described for the tuners. The vacuum ports will consist of slotted holes that penetrate the copper cavity walls and that were designed to maximize gas conductance while preventing RF leakage into the pumps. O-rings will provide the vacuum sealing for these ports.

RFQ Assembly

The RFQ modules are easily aligned during assembly as the ends are designed to be self-aligning through the use of dowel pins embedded in the walls at the ends. The bolted end connections are sufficiently strong and stiff such that the fully assembled RFQ can be supported as a single unit. This characteristic allows the RFQ body to be supported using a simple kinematic 6-strut system that cannot impart any direct bending stresses on the assembled RFQ. A CAD image of the full, four module RFQ is shown in Fig. 6.

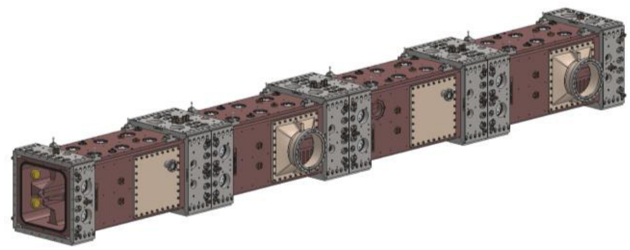

Figure 6: CAD model of the entire RFQ.

THERMAL PERFORMANCE

A series of RF, thermal and structural analyses were performed during the design of the PXIE RFQ. The details of these analyses, which were carried out using ANSYS [3], are provided in [4]. 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. The peak temperatures in the cavity copper were found to be only 4 to 5°C higher than the cooling water inlet temperature.

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 tip cooling water temperature. For uniform water temperature control, the shift would only be -2.8 kHz/°C.

SUMMARY

LBNL has completed the final RFQ design for the Project X Injector Experiment at Fermilab. The overall design scheme was presented in this paper. Construction of the actual RFQ modules is now under way at LBNL and is expected to be completed by the end of 2014. Details of the fabrication progress can be found in [5].

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